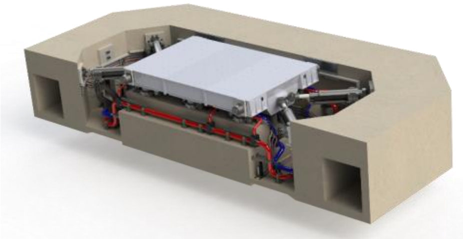
National Science Foundation

University of California at San Diego
NHERI
Natural Hazards Engineering Research Infrastructure

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Structural Engineering

Joint Academia-Industry NHERI@UC San Diego Workshop

Joel P. Conte, Professor of Structural Engineering,
University of California, San Diego



May 19, 2023

University of California, San Diego

General Housekeeping Items

- PDF copies of the presentations in this workshop are available to download here:

  https://drive.google.com/drive/folders/1Bu49Sf7b9Rk7IOtEPTxIbndJsSldA62h

- To request PDH Credit Certificate, please contact:

  Dr. Koorosh Lotfizadeh

  E-mail: klotfiza@ucsd.edu

- For any problems and technical difficulties, please contact:

  Dr. Koorosh Lotfizadeh

  E-mail: klotfiza@ucsd.edu

Workshop Program

Friday, May 19, 2023 ---- Morning

Time (PST)	Topic	Speaker
7:30 – 8:00 am	Registration, Speaker Check-in, Breakfast	
8:00 – 8:15 am	Welcome and Introduction	Joel Conte, Dept. of Structural Engineering, UC San Diego
8:15 – 9:15 am	NHERI@UC San Diego: Facility Description, Capabilities, Past Projects, and Research Enabled by LHPOST6	Joel Conte
9:15 – 9:30 am	Universal Base Frame for LHPOST6	Machel Morrison Dept. of Structural Engineering, UC San Diego
9:30 – 9:50 am	Keynote Presentation #1 (remote): Dynamic Testing, Model Calibration and Validation for Concrete Dams	Larry K. Nuss Nuss Engineering, LLC Retired from Bureau of Reclamation
9:50 – 10:10 am	Dams Discussion	
10:10 – 10:30 am	Break	
10:30 – 10:50 am	Keynote Presentation #2: Building Structures	David Mar David Mar and Associates
10:50 – 11:10 am	Building Structures Discussion	
11:10 – 11:30 am	Keynote Presentation #3: Seismic Testing for Transportation	Tim Ingham TY Lin
11:30 – 11:50 am	Transportation Infrastructure Discussion	
11:50 – 12:10 pm	Keynote Presentation #4: Lifelines and Utilities	Brad Wham University of Colorado, Boulder
12:10 – 12:30 pm	Lifelines and Utilities Discussion	
12:30 – 1:40 pm	Lunch	

Workshop Program

Friday, May 19, 2023 ---- Afternoon

Time (PST)	Topic	Speaker
1:40 – 2:00 pm	Keynote Presentation #5: Geostructures	Armin Stuedlein Oregon State University
2:00 – 2:20 pm	Geostructures Discussion	
2:20 – 2:40 pm	Keynote Presentation #6: Tilt Up and Precast Structures	Marc Maguire University of Nebraska, Lincoln
2:40 – 3:00 pm	Tilt Up and Precast Structures Discussion	
3:00 – 3:30 pm	Summary of Discussion Sessions and Concluding Remarks	Joel Conte
3:30 – 6:00 pm	Visit to NHERI@UC San Diego Shake Table Facility and Happy Hour with Dinner from Belinda's	

Workshop Objectives

- Showcase the features and capabilities of the newly upgraded (6-DOF) LHPOST6 supporting advanced earthquake engineering research.
- Disseminate information on the use of the NHERI@UC San Diego Experimental Facility to conduct state-of-the-art research and experimentation in natural hazards mitigation.
- Promote academia-industry collaborations and identify high priority research needs, which would benefit from the newly upgraded NHERI@UC San Diego Experimental Facility.
- Identify and formulate grand challenge research needs to advance the science, technology and practice in earthquake disaster mitigation and prevention, and to improve seismic design codes and standards.
- Identify and develop opportunities to utilize the NHERI@UC San Diego Experimental Facility.
- Brainstorm on example uses of the facility to solve grand challenges in earthquake engineering.
- Stimulate specific thematic research collaborations between academia and industry taking advantage of the unique LHPOST6 NHERI Experimental Facility.

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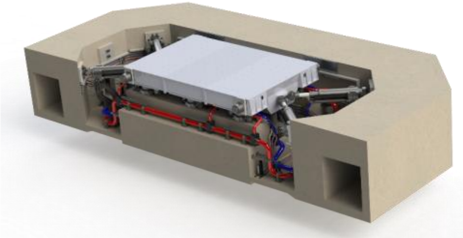
Structural Engineering

NHERI@UC San Diego: Facility Description and Capabilities – Research Enabled by LHPOST6

Joel P. Conte
Dept. of Structural Engineering, UC San Diego

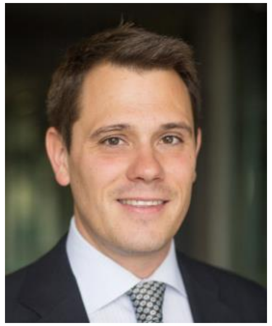


Joint Academia-Industry NHERI@UC San Diego Workshop

May 19, 2023
University of California, San Diego

UC San Diego NHERI Renewal Team

Joel Conte
PI, Site Admin.



John McCartney
Co-PI, Site User Services

Machel Morrison
Co-PI, Site Operations

José Restrepo
Co-PI, Site Performance

Lelli Van Den Einde
Co-PI, ECO

Koorosh Lotfizadeh
Site Operation Mgr.

Abdullah Hamid
Dev. Engineer

TBN
Administrative Assist.

Anton Del Rosario
Financial Mgr.

Chin-Ta Lai
Ph.D. Student

Andres Rodriguez
Ph.D. Student

Robert Beckley
IT Manager

Alex Sherman
Dev. Tech./Safety Ofc.

Jeremy Fitcher
Dev. Tech.

Tara Hutchinson
Cap. Bld. Partn.

Gilberto Mosqueda
Cap. Bld. Partn.

Benson Shing
Cap. Bld. Partn.

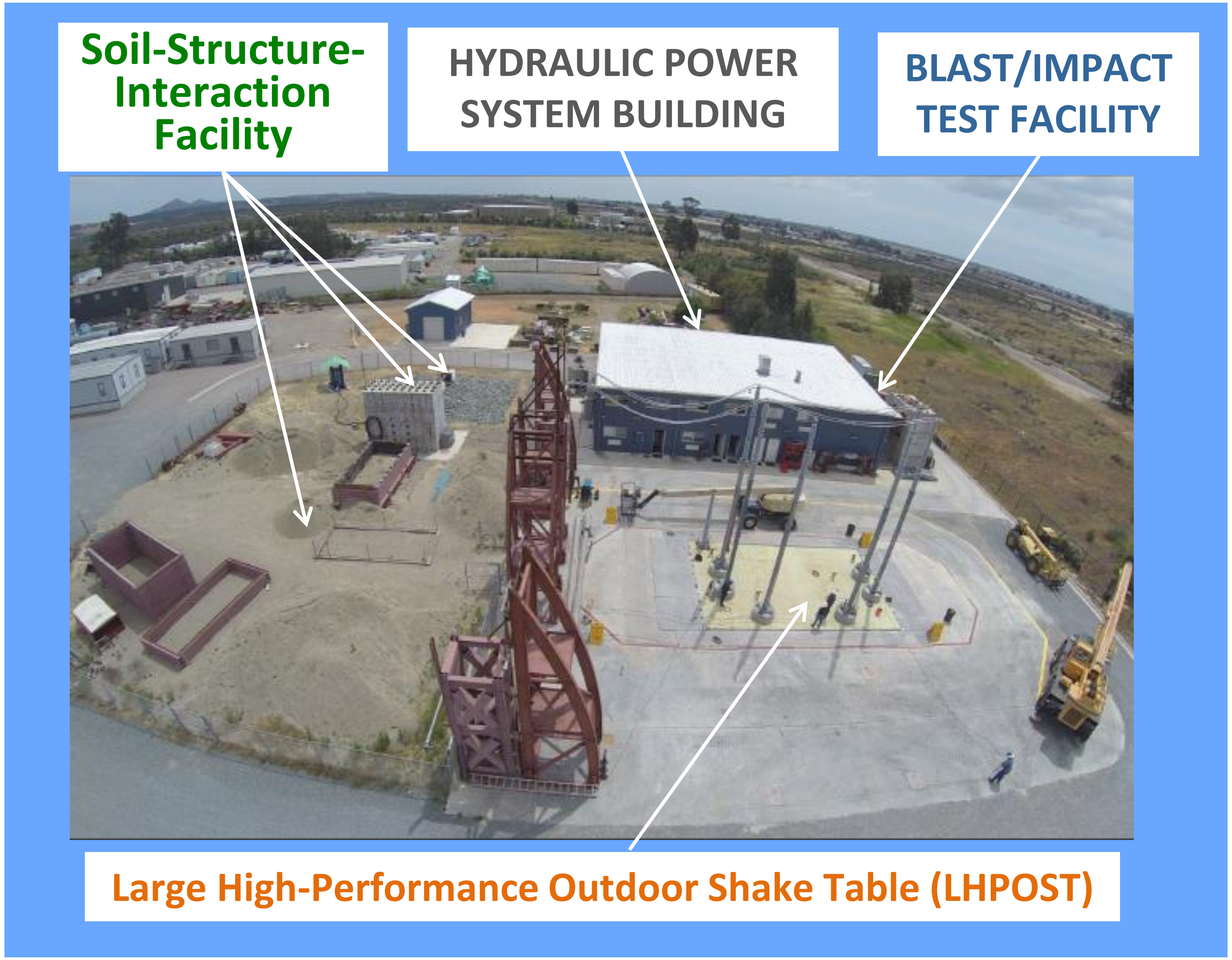
Georgios Tsampras
Cap. Bld. Partn.

Outline

- Overview of Englekirk Structural Engineering Center
- Large High-Performance Outdoor Shake Table (LHPOST)
- Select Set of Shake Table Tests Performed on the NHERI@UC San Diego Shake Table
- Six Degree-of-Freedom (6-DOF) Upgrade of the LHPOST into the LHPOST6
  - Design and Description of the Upgrade
  - Performance of the LHPOST6
- New Research Opportunities Made Possible by the LHPOST6

Overview of Englekirk Structural Engineering Center (ESEC)

Englekirk Structural Engineering Center (ESEC)



Soil-Foundation-Structure Interaction Facility

Bridge Abutment - Soil Interaction (Caltrans)

Pile – soil interaction (Port of Los Angeles)

IAS Accreditation of ESEC

INTERNATIONAL ACCREDITATION SERVICE®

CERTIFICATE OF ACCREDITATION

This is to attest that

ENGLEKIRK STRUCTURAL ENGINEERING CENTER

10201 POMERADO ROAD
SAN DIEGO, CA 92131

Testing Laboratory TL-356

has met the requirements of AC89, *IAS Accreditation Criteria for Testing Laboratories,* and has demonstrated compliance with ISO/IEC Standard 17025:2005, *General requirements for the competence of testing and calibration laboratories.* This organization is accredited to provide the services specified in the scope of accreditation maintained on the IAS website (www.iasonline.org).

This certificate is valid up to April 1, 2019.

This accreditation certificate supersedes any IAS accreditation bearing an earlier effective date. The certificate becomes invalid upon suspension, cancellation or revocation of accreditation. See www.iasonline.org for current accreditation information, or contact IAS at 562-364-8201.

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Raj Nathan
President

15-12065

Large High-Performance Outdoor Shake Table (LHPOST)

- **Design and Construction of the LHPOST (2001 – 2004)**
  - Funded by the National Science Foundation (NSF) under the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) program with additional financial resources from the Department of Defense (Technical Support Working Group - TSWG) and UC San Diego
- **NEES@UC San Diego Shake Table (2004 – 2014)**
  - Under the NEES NSF program
- **NHERI@UC San Diego Shake Table (2016 – 2022)**
  - The Natural Hazard Engineering Research Infrastructure (NHERI) program at the National Science Foundation (NSF)
- **6-DOF Upgrade of the NHERI@UC San Diego Shake Table (2016 – 2022)**
  - Funded by NSF with additional financial resources from UC San Diego
- **NHERI@UC San Diego Shake Table (2022 – 2025) --- RENEWAL**
  - Under the NHERI NSF program

Objectives of the NHERI@UC San Diego Experimental Facility

The **vision for the NHERI@UC San Diego Shake Table experimental facility** is rooted on **four critical needs** for advancing the science, technology, and practice in earthquake disaster mitigation and prevention:

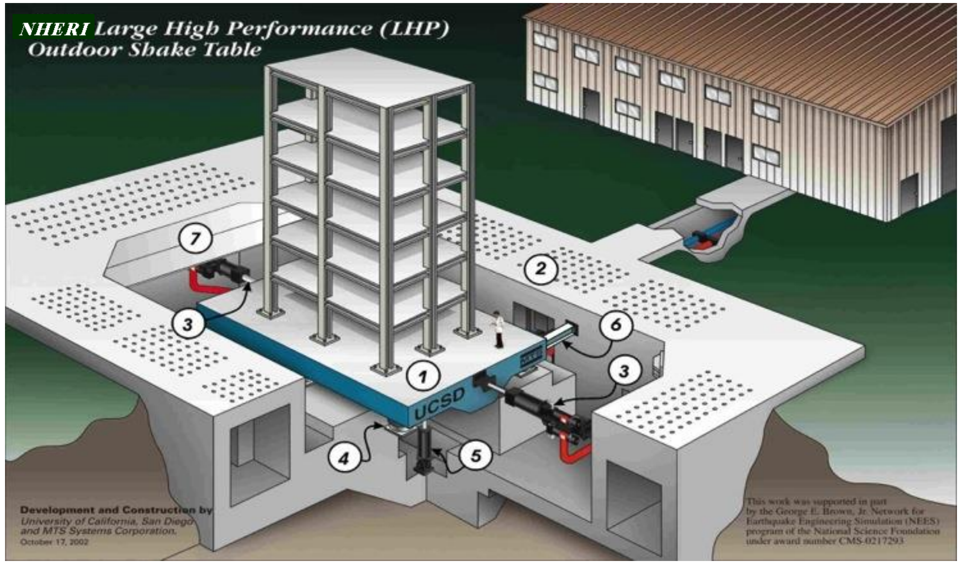
(1) Fundamental knowledge for understanding the **system-level behavior** of **buildings**, **critical facilities**, **bridges**, and **geo-structures** during earthquakes, **from the initiation of damage to the onset of collapse,** including the **effects of soil-structure interaction** and the **contributions of lateral and gravity load-resisting systems** and **non-structural systems**.

(2) Experimental data to support the **development, calibration and validation of high-fidelity physics-based computational models** of structural/geotechnical/soil-foundation-structural systems that will **progressively shift the current reliance on physical testing to model-based simulation** for the design and performance assessment of civil infrastructure systems subjected to earthquake hazards.

(3) **Data and fragility information** to achieve the **full realization of Performance-Based Design**.

(4) **Ultimate validation tests** for protective systems, retrofit methods, and the use of innovative materials/components/systems, and construction/manufacturing methods that can protect civil infrastructure systems against earthquake hazards.

1-DOF Large High-Performance Outdoor Shake Table (LHPOST) 2004-2019



Performance Characteristics of LHPOST in Past 1-DOF Configuration (2004 – 2019)	
Designed as a 6-DOF shake table, but built as a 1-DOF system to meet funding available	
Stroke	**±0.75m**
Platen Size	40 ft × 25 ft (12.2 m × 7.6 m)
Peak Velocity	**1.8 m/sec**
Peak Acceleration	4.7g (bare table condition); 1.2g (4.0MN/400 tonf rigid payload)
Frequency Bandwidth	**0-33 Hz**
Horizontal Actuators Force Capacity	**6.8 MN (680 tonf)**
Vertical Payload Capacity	**20 MN (2,000 tonf)**
Overturning Moment Capacity	50 MN-m (5,000 tonf-m)

Large High-Performance Outdoor Shake Table (LHPOST)

- Designed to permit accurate simulation of severe earthquake ground motions and, particularly, strong near-source ground motions.
- Enables seismic testing of full- or very large-scale structural specimens of any height and a wide range of footprint dimensions.
- Table designed in 2001-2002, built in 2002-2004, and commissioned on October 1, 2004, as a shared-use experimental facility of the NSF NEES Network.
- 34 major research and commercial projects were conducted in 15 years of operation (2004 – 2019):
  - Reinforced concrete buildings and bridge column
  - Precast concrete parking structure
  - Unreinforced and reinforced masonry building structures
  - Metal and light-steel building structures
  - Woodframe/timber dwellings and buildings
  - Wind turbine
  - Soil retaining walls, spillway retaining walls
  - Underground structures (deep and shallow)

Capabilities/Provisions of the NHERI@UC San Diego LHPOST

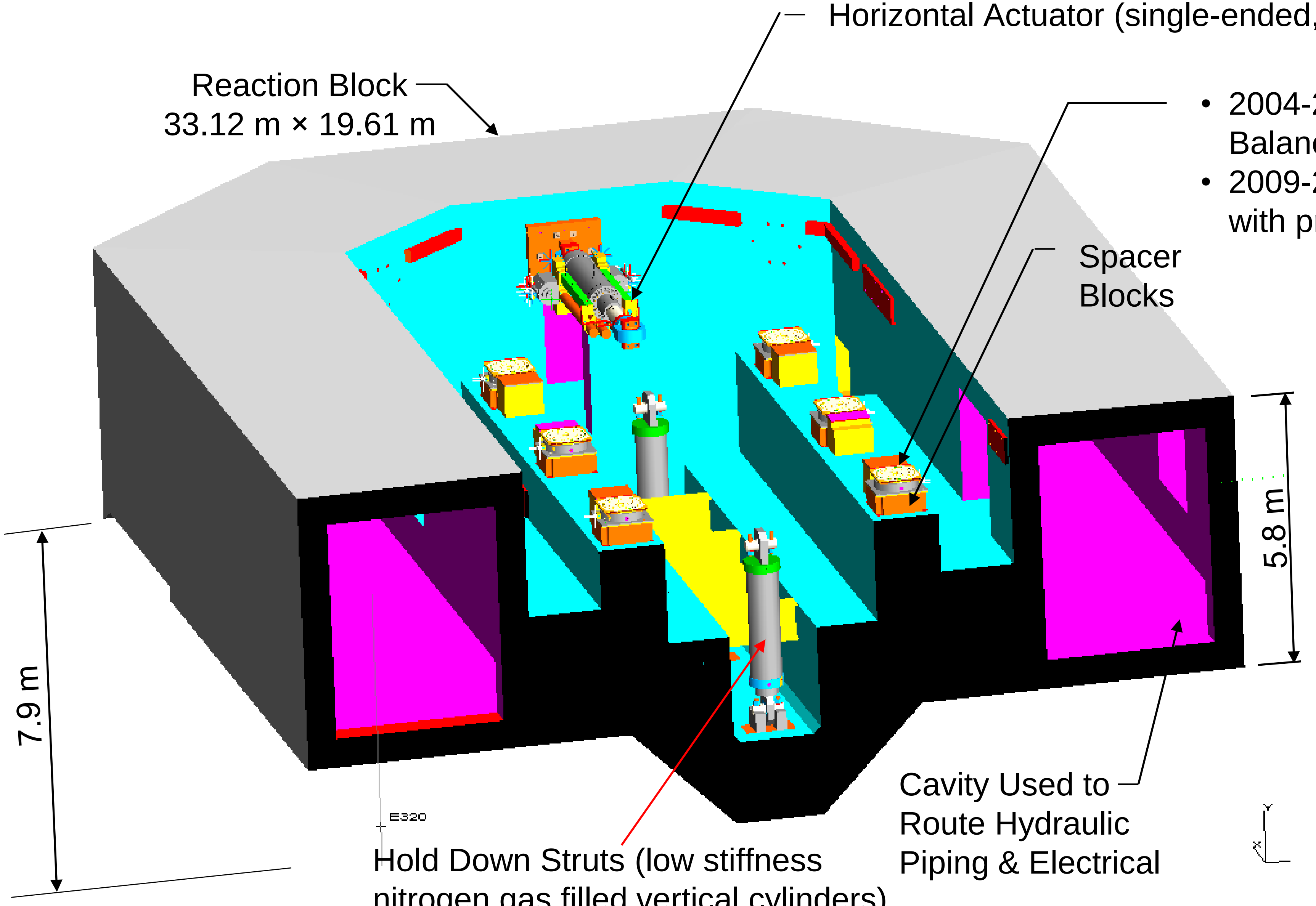
- **Simulation of near-source earthquake ground motions** which involve large acceleration, velocity and displacement pulses, **including six ground motion components (three translational and three rotational).**

- Seismic testing of **extensively instrumented large/full-scale structural specimens** under extreme earthquake loads at near real-world conditions.

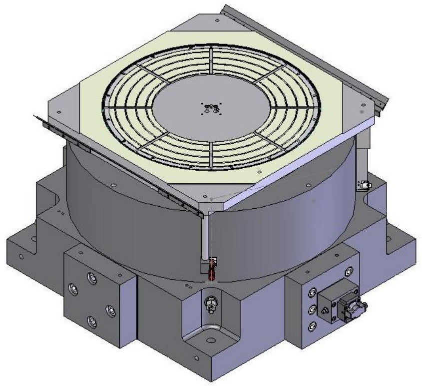
- Seismic testing of **extensively instrumented large-scale geotechnical and soil-foundation-structural systems** by using the shake table in combination with large soil boxes.

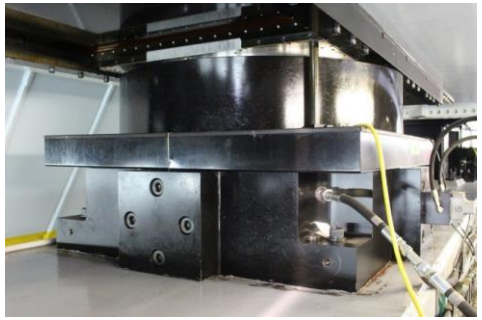
- **Education** of graduate, undergraduate, and K-12 students from diverse backgrounds, as well as news media, policy makers, infrastructure owners, insurance and the general public, **about natural disasters** and on the urgency of the **nation's efforts to develop effective technologies and proper policies to prevent these natural events from becoming societal disasters**.

1-DOF LHPOST (2004 –2019)

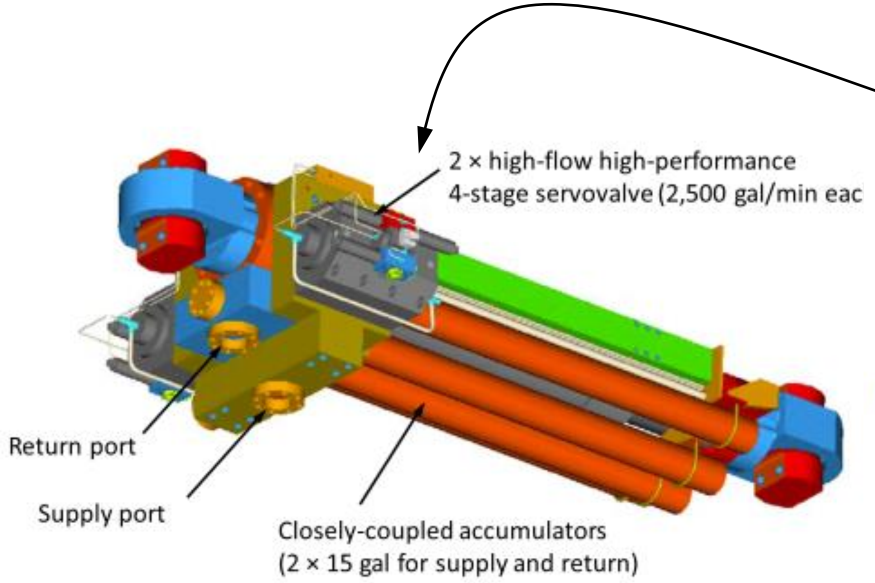


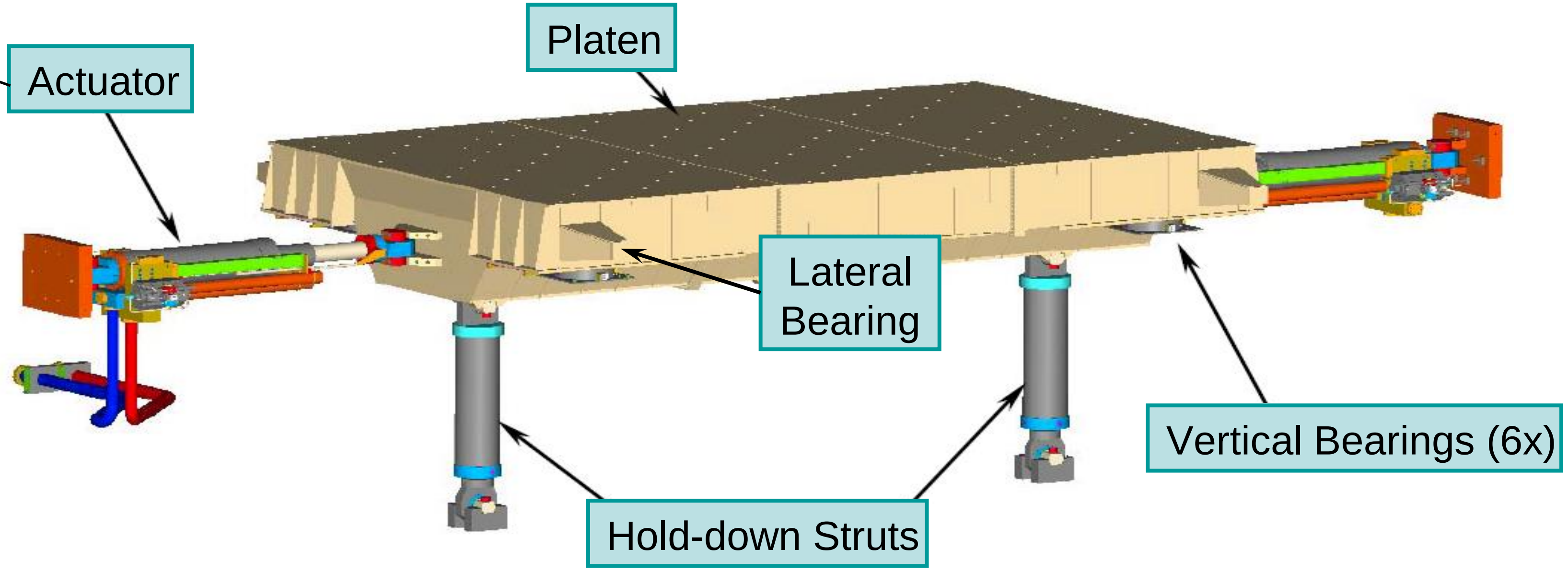
- 2004-2009: Vertical Pressure Balance Bearings
- 2009-2019: Actuators (non-ported) with pressure balanced bearings



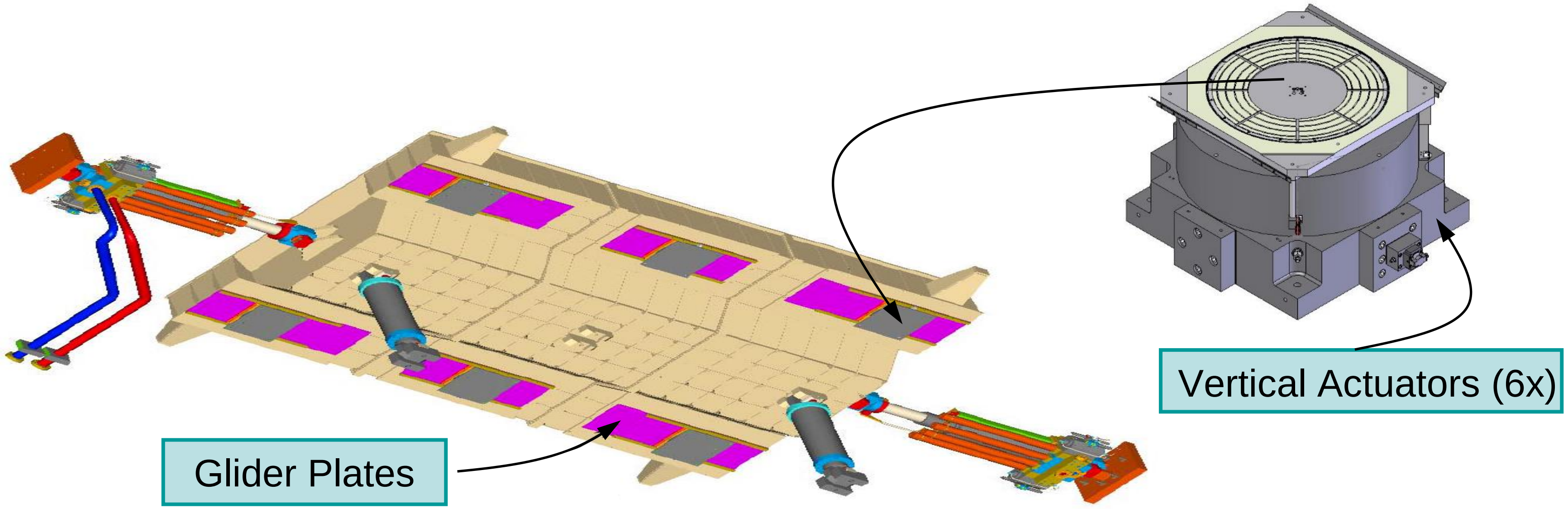


Mechanical and Servo-Hydraulic Components (1-DOF LHPOST: 2004 –2019)



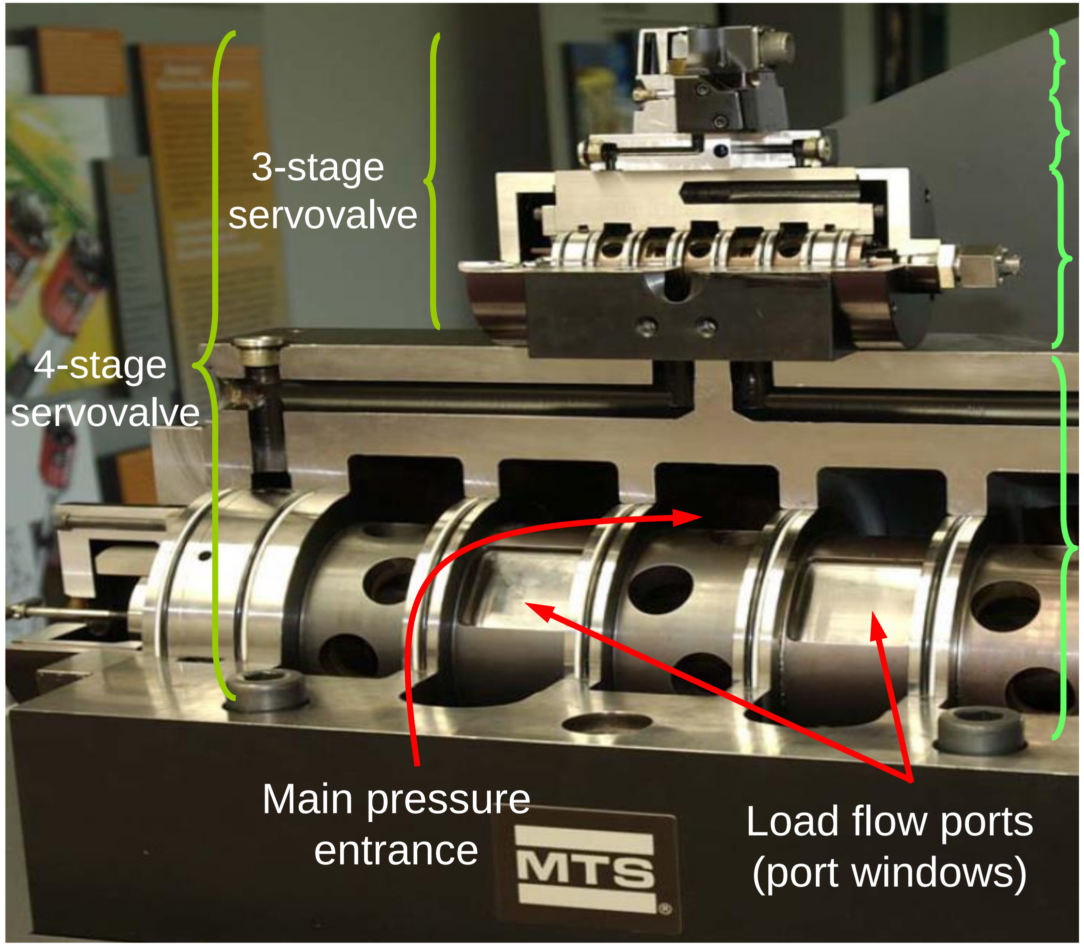


Horizontal Actuators Specification	
Dynamic stroke	+/- 0.75 m
Force Capacity (Tension/Compression)	2.7 MN / 4.2 MN
Rod diameter	0.3048 m
Piston Diameter	0.5080 m
Tension Area	0.1297 m^2
Compression Area	0.2027 m^2
Peak Extend Flow Rate	21,890 lt/min
Peak Retract Flow Rate	14,010 lt/min



High-Flow High-Performance Servovalves of Horizontal Actuators

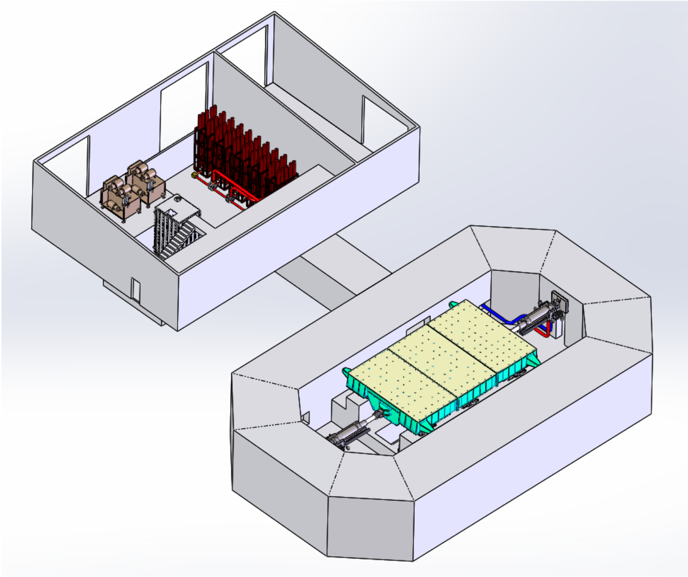
Servovalves (Qty. 2E + 2W)	
Pilot 2nd Stage Rating (Manufacturer Moog)	**19 lt/min**
Pilot 3rd Stage Rating	**630 lt/min**
4th Stage Flow Rating	**10,000 lt/min (2,500 gpm)**
Port Area Ratios	1:0.8:0.64:0.5
Valve Sleeve Windows Area Ratio	1:0.64

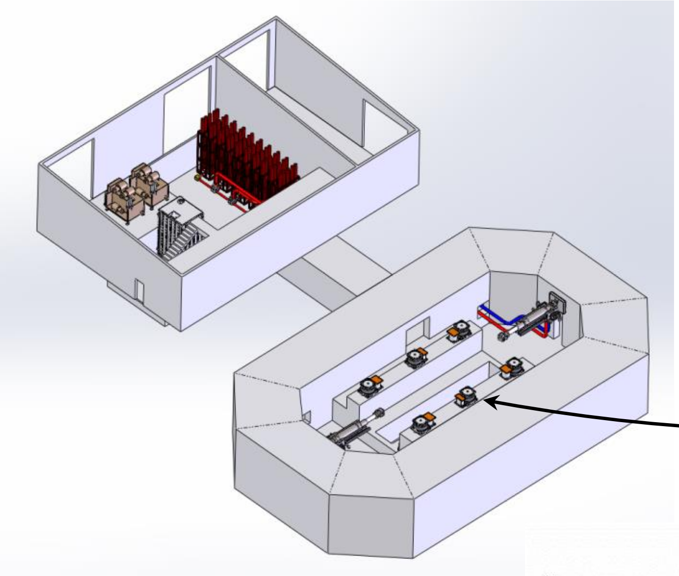


1st stage
2nd stage
Pilot valve
3rd stage
4th stage (main stage)

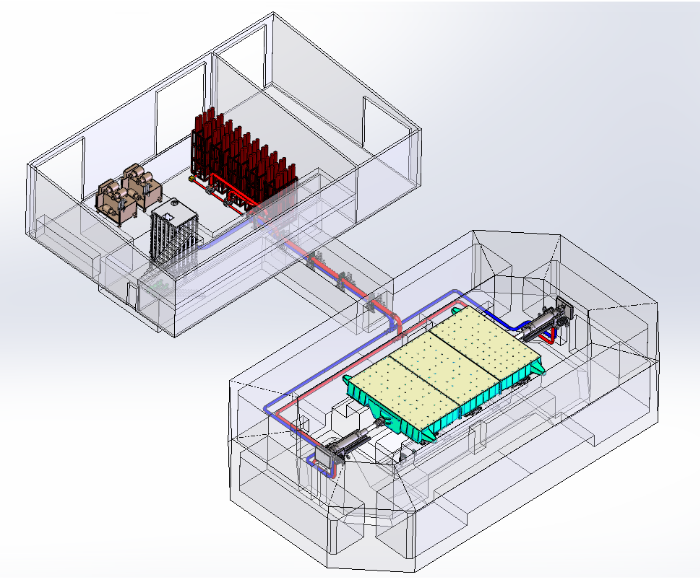
Courtesy of MTS Systems Corporation

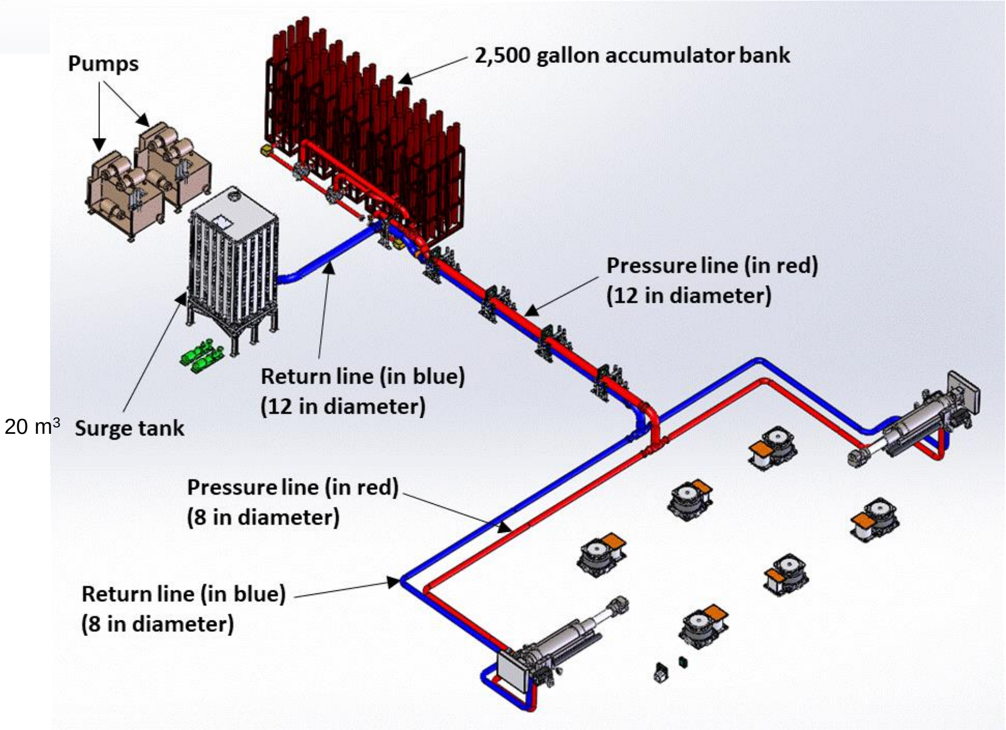
Hydraulic Power System of 1-DOF LHPOST (2004 –2019)





- 2004-2009: **Pressure balanced bearings**
- 2009-2019: **Actuators (non-ported)** with pressure balanced bearing



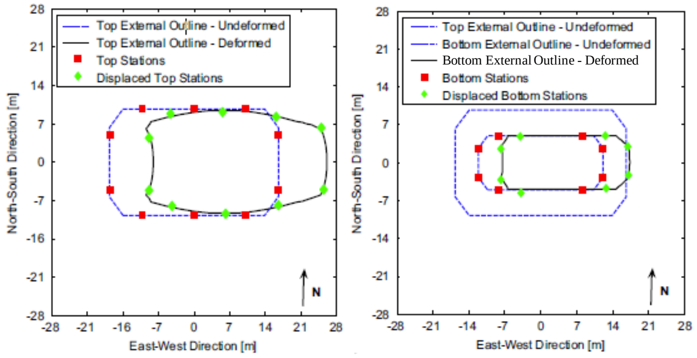


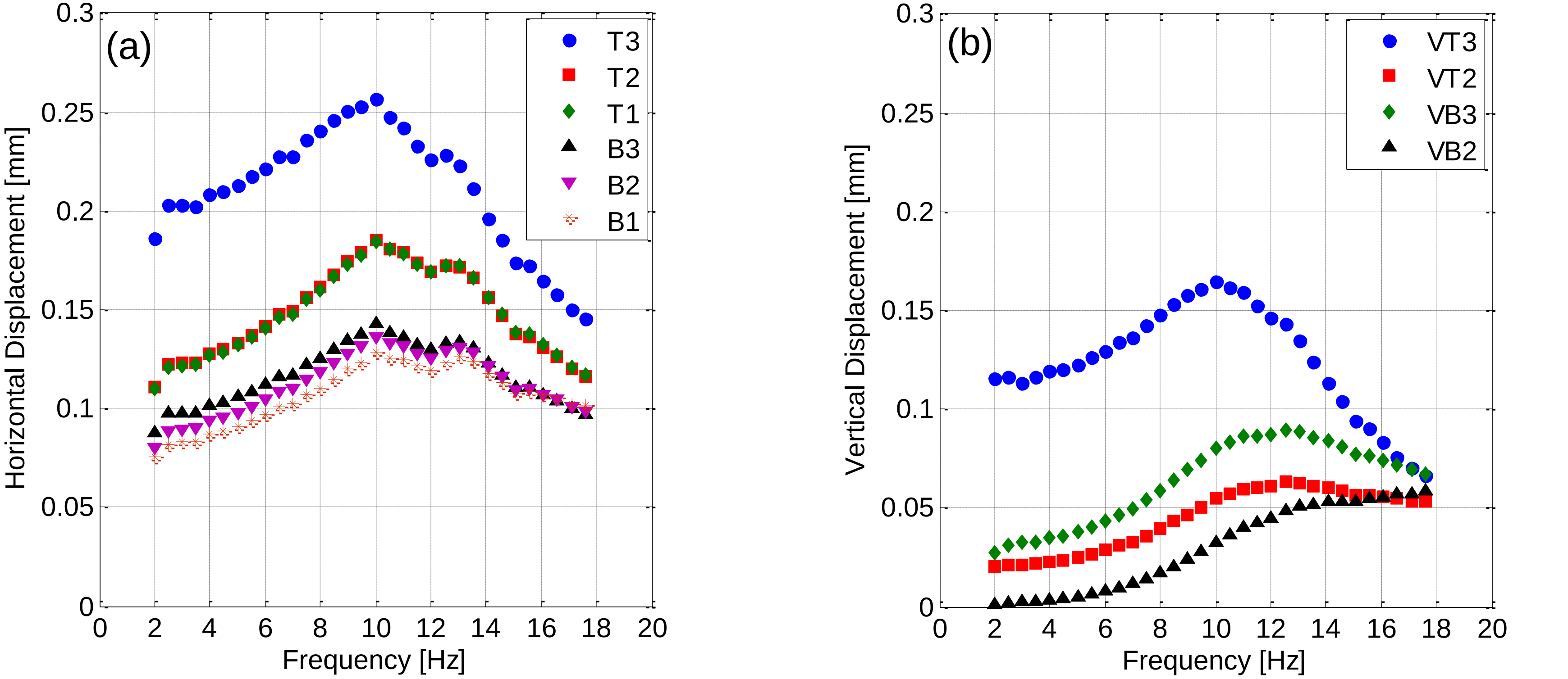
Bare Table Motion (1-DOF LHPOST)

Reaction Mass/Block

- Stiff soil conditions
- High radiation damping (effective damping ratio between 32% and 42%)
- Light reaction mass: 43.8 MN (4,380 tonf) for a vertical payload capacity of 20 MN (2,000 tonf).

Frequency Response Functions of Reaction Mass/Block





Amplitudes of the EW (a) and vertical (b) frequency response functions of the reaction block for EW excitation. The results shown are based on Test 2 and correspond to scaled displacement amplitudes for a harmonic force of constant amplitude 6.8 MN.

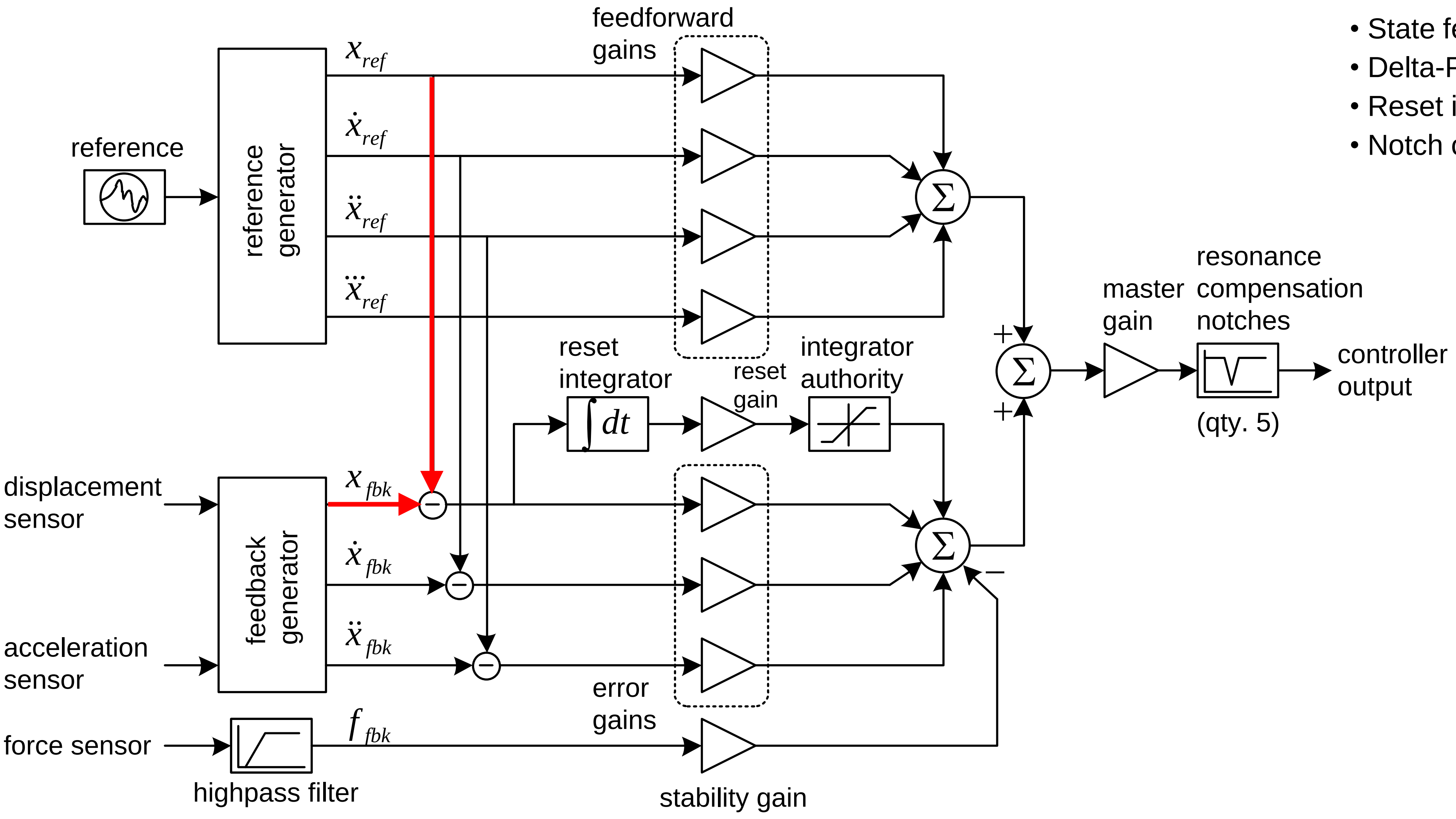
MTS Three-Variable Controller (TVC)

- **MTS Controller Model 469D** used on all large shake tables manufactured by MTS worldwide.
- TVC is a linear **state variable controller**. The three **state variables controlled by TVC** are:
  - Displacement
  - Velocity
  - Acceleration

  TVC can be set to run under displacement, velocity or acceleration mode.
- TVC has **special features to compensate for dynamic linear/nonlinear sources of signal distortions** within the system for both harmonic and broadband command signals:
  - Amplitude/phase control (APC)
  - Adaptive harmonic cancellation (AHC)
  - Adaptive inverse control (AIC)
  - On-line iteration (OLI): Iterative signal matching technique
  - Notch filters
- Depending on the control mode, only one state variable becomes the **primary control variable** with the others serving only as compensation signals to improve the damping and stability of the system.

MTS 469D – Three-Variable Controller (TVC)

TVC = State-Variable Control + Extras



Components:

- State-variable controller
- State reference generator
- State feedback observer
- Delta-P stabilization
- Reset integrator
- Notch compensation

Courtesy of MTS Systems Corporation

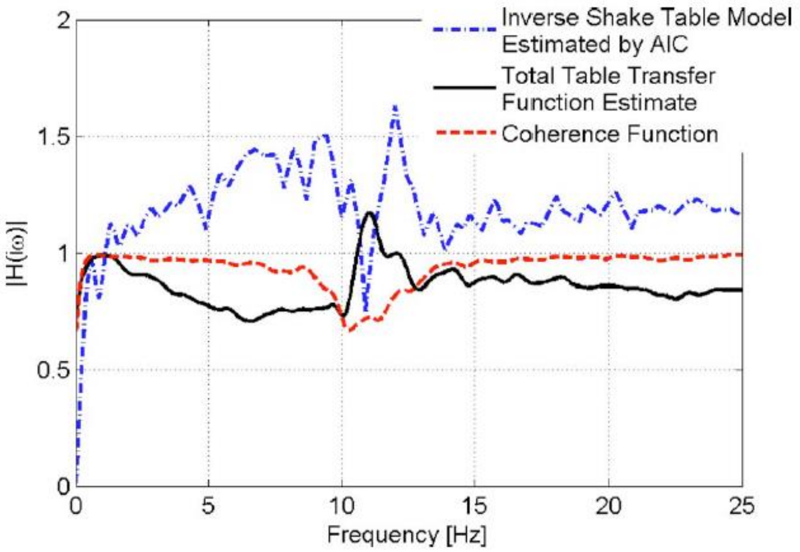
Tuning of LHPOST Controller (MTS 469D)

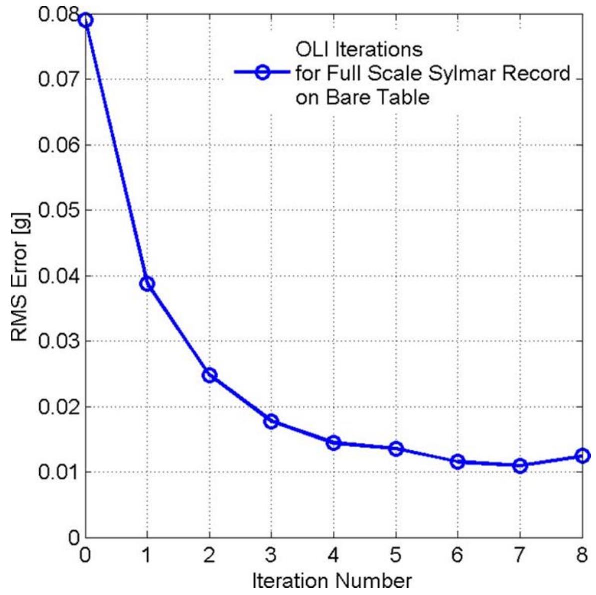
Tuning: Process of adjusting multiple control parameters (e.g., feedback and feedforward gains) and of preconditioning the input motion (through OLI) to optimize signal reproduction (tracking) capability of the shake table system.

Step 1: Iterative process in which the control parameters of the controller are manually adjusted iteratively in small increments while the (bare or loaded) table is in motion, until the total table transfer function (estimated recursively) is deemed satisfactory.

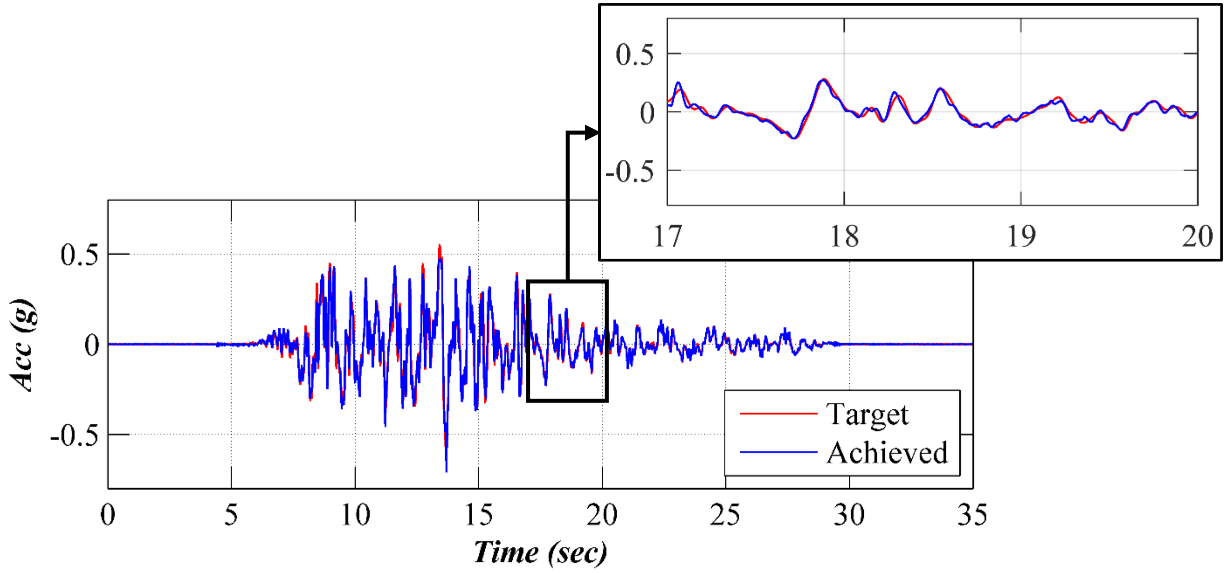
Step 2: Estimation of the inverse model of the plant using the adaptive inverse controller (AIC) technique.

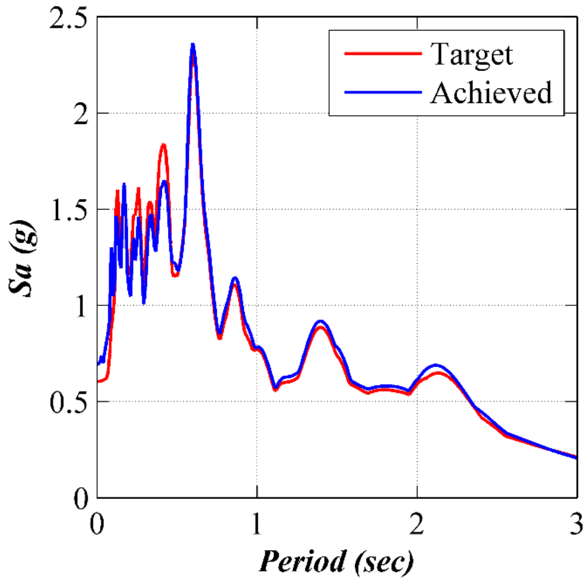
Step 3: Application of iterative time history matching technique called online iteration (OLI). The command input to the shake table controller (drive file) is repeatedly modified to optimize the match between the actual table motion and the desired/target motion (or reference signal).

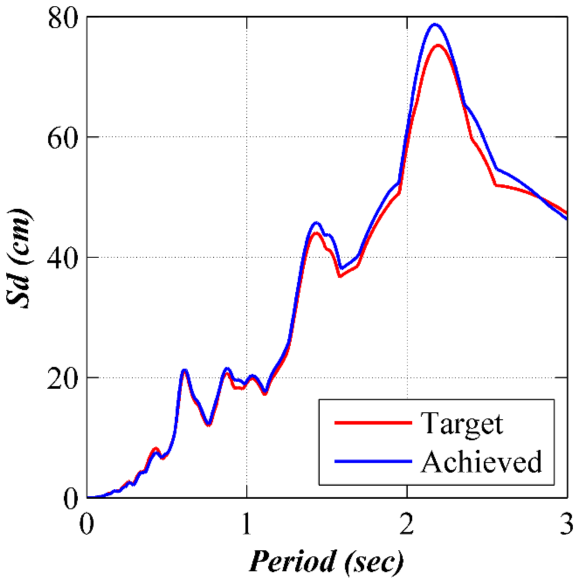




Tracking Performance of LHPOST (1-DOF)







1994 Northridge Earthquake
Canoga Park (comp. 196)
Amplitude scaling: 1.55

Instrumentation of LHPOST

- **Data Acquisition**
  - **13 DAQ nodes with 64 channels each** sampling up to **25.6 kS/sec** per channel with **24-bit A/D resolution**
- 251 MEMS-based **Accelerometers** (±5g and ±10g)
- 305 Linear **Displacement Transducers** (1 to 20 in)
- 154 **String Potentiometer** Displacement Transducers (2 to 120 in)
- 28 **Inclinometers** (±15 deg)
- Strain Gages purchased per project as needed
- 4 **Load Jacks**
- 31 **Load Cells** (up to 20,000 lbs)
- 32 **Soil Pressure Transducers**
- **GNSS System** with 10 Receivers Operating at **100 Hz**
- **High-Speed Cameras**
  - DJI Phantom 4 Pro Drone, 15 GoPros 4K and 1080p, 4 Axis 240Q/241Q video servers streaming, 3 IQeye streaming/time lapse video (all at **30 fps**)
- **Fully Configured, End-to-End, Live Video Streaming Production System**
  - NHERI@UC San Diego is on social media (youtube, facebook, twitter)
- **Calibration Equipment** for Data Acquisition Systems and Sensors

Selected Shake Table Tests Performed on the LHPOST (1-DOF)

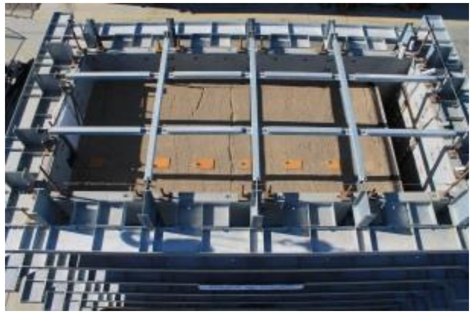
Select Set of Specimens Tested on the LHPOST (1-DOF)









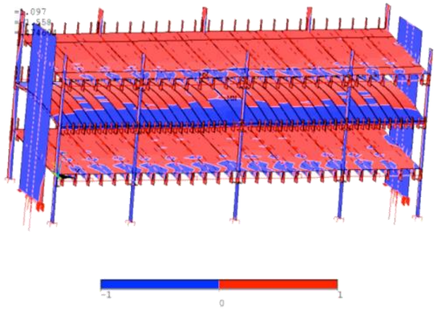




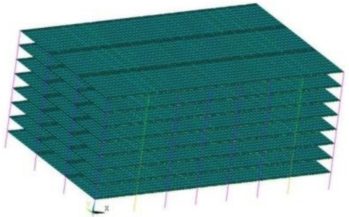
Integrated Experimental-Analytical Approach

Experimental Research
- Materials
- Structural components
- Structural systems

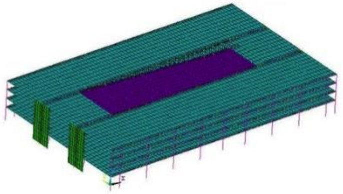
Computational Simulation
- Model development
- Model calibration
- Model validation



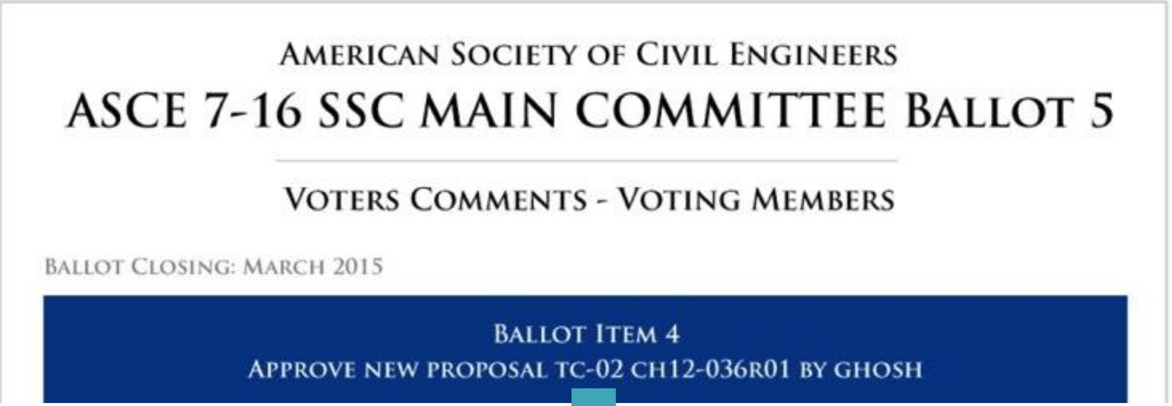
Design Provisions and Assessment Methods
- Development
- Verification through numerical simulation



8-STORY OFFICE BUILDING



4-STORY PARKING STRUCTURE



AMERICAN SOCIETY OF CIVIL ENGINEERS

ASCE 7-16 SSC MAIN COMMITTEE BALLOT 5

VOTERS COMMENTS - VOTING MEMBERS

BALLOT CLOSING: MARCH 2015

BALLOT ITEM 4

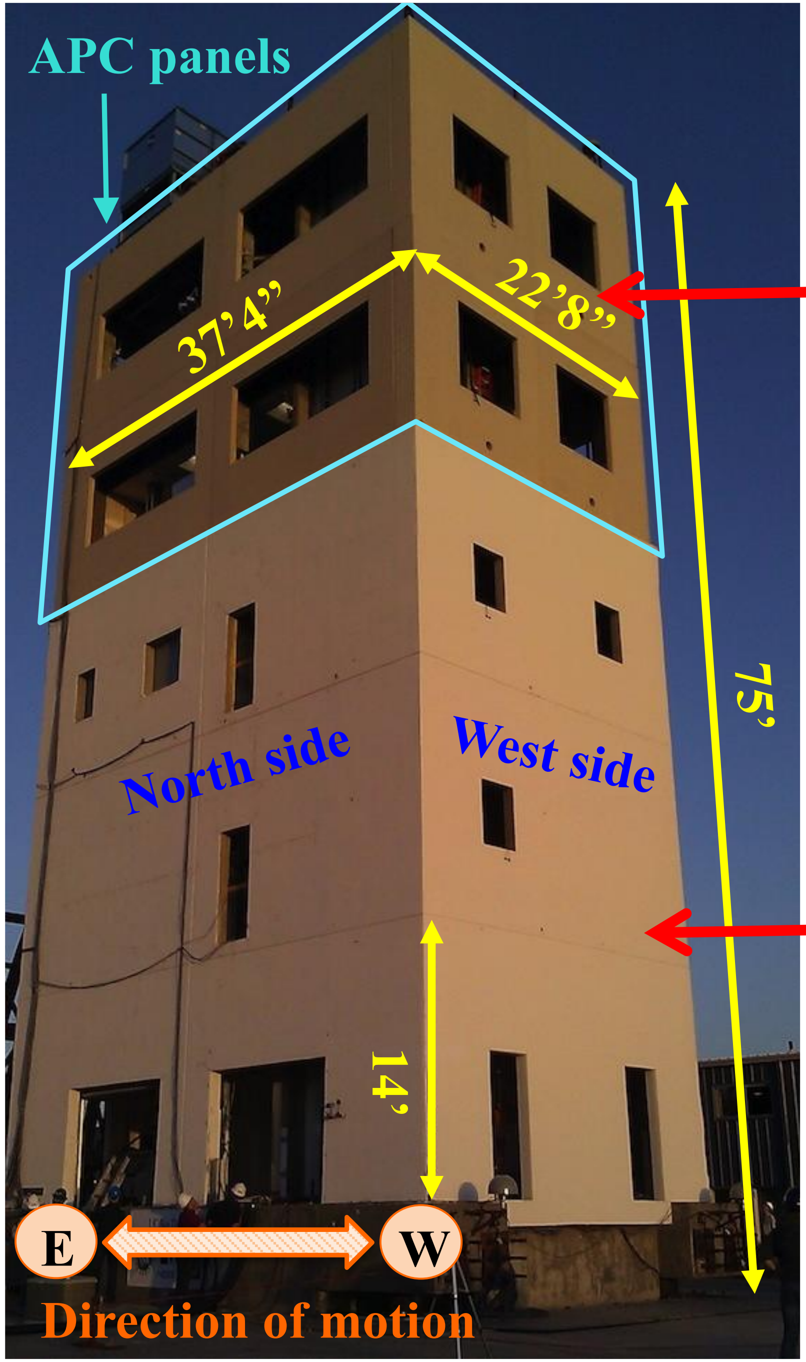
APPROVE NEW PROPOSAL TC-02 CH12-036R01 BY GHOSH

SUSTAINABLE AND SEISMIC/DISASTER RESILIENT BUILT ENVIRONMENT

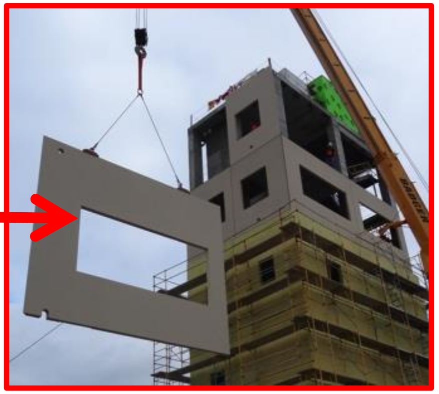
Full-scale Structural and Non-structural Building System Performance During Earthquakes

PI – Prof. Tara Hutchinson, UC San Diego

Exterior Facades



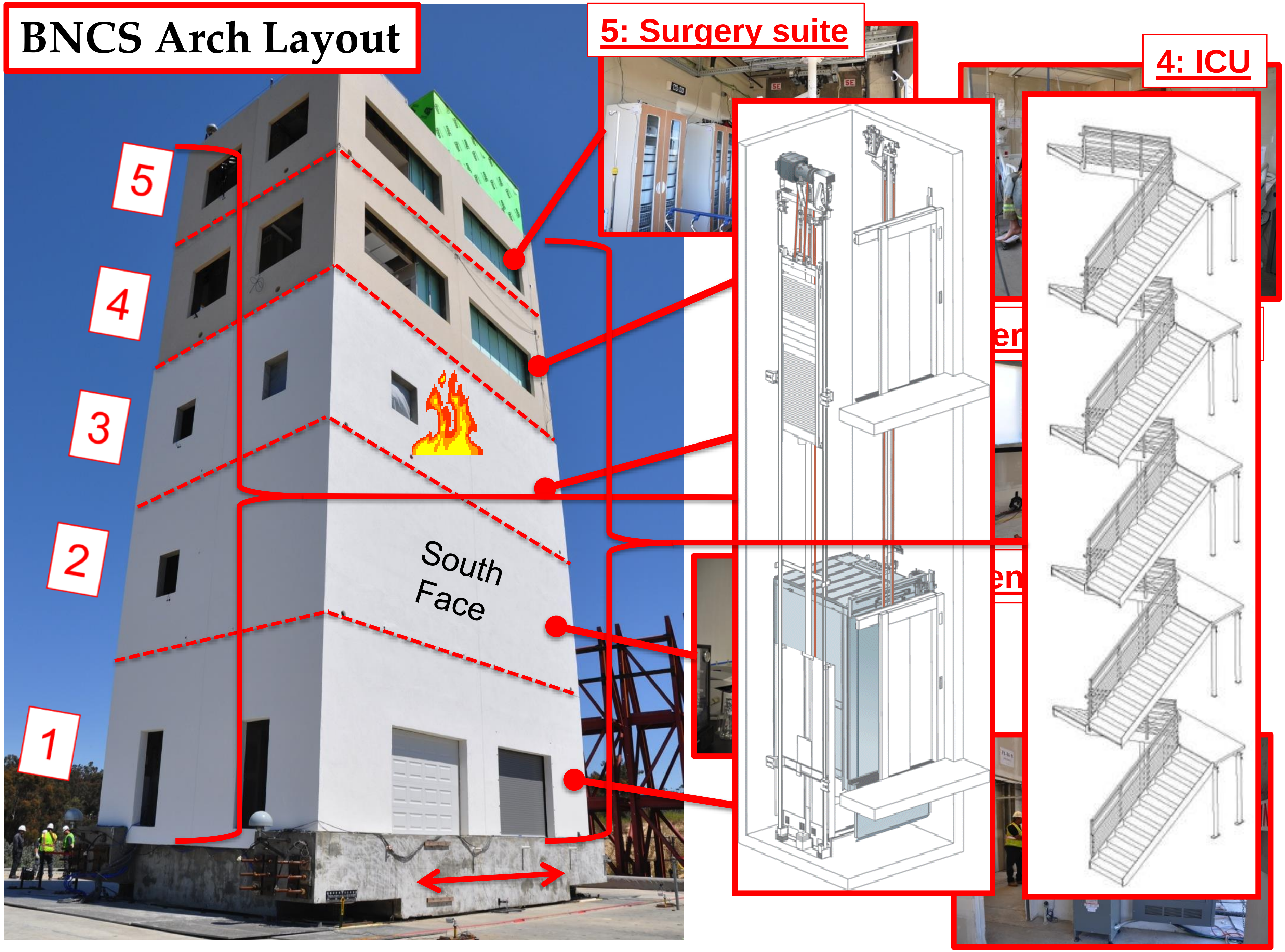
Architectural Precast Concrete Cladding



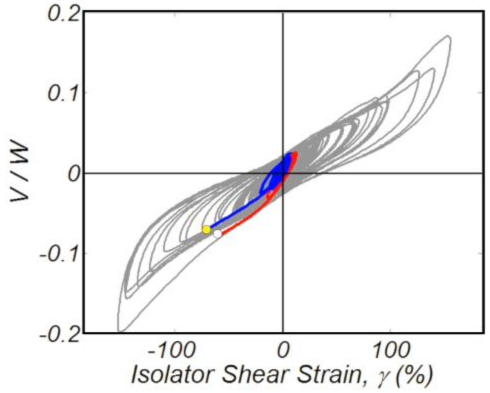
Balloon-framed metal stud+EIFS

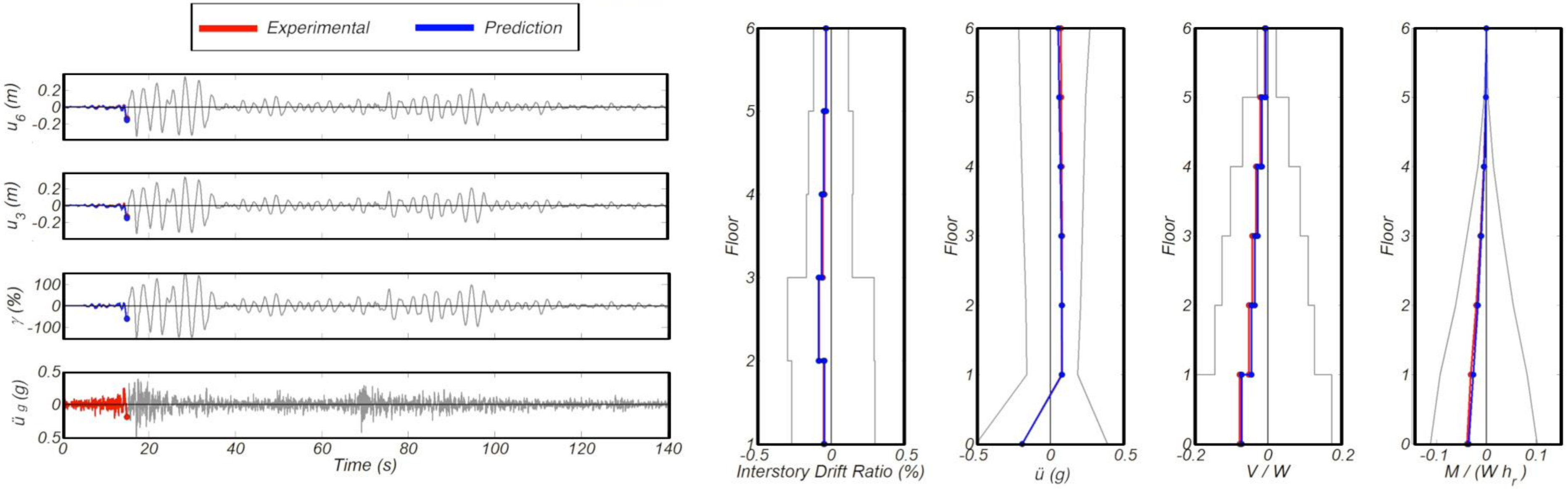
NW View

BNCS Arch Layout



Full-Scale Structural and Nonstructural Building System Performance – Base Isolated

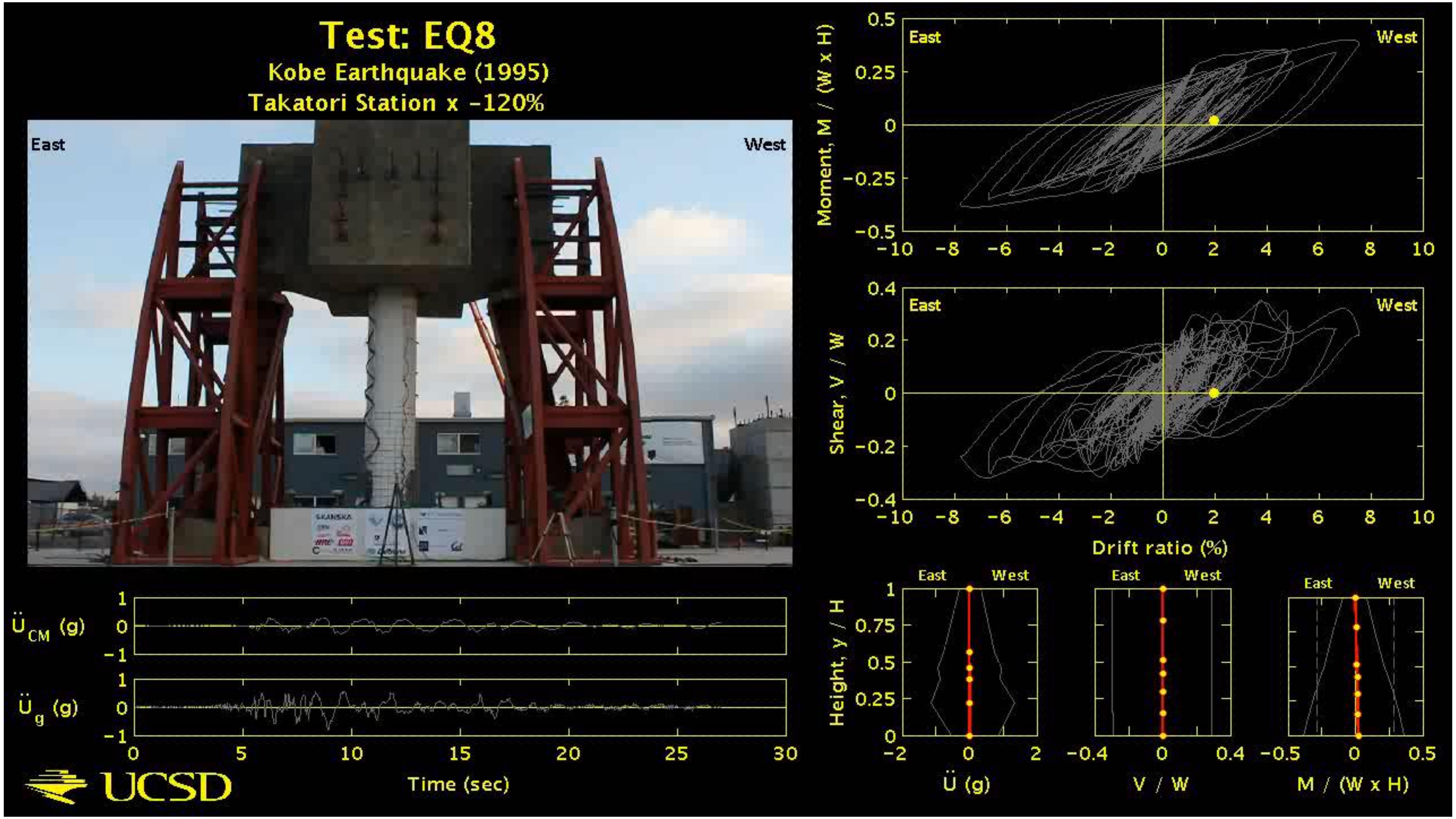


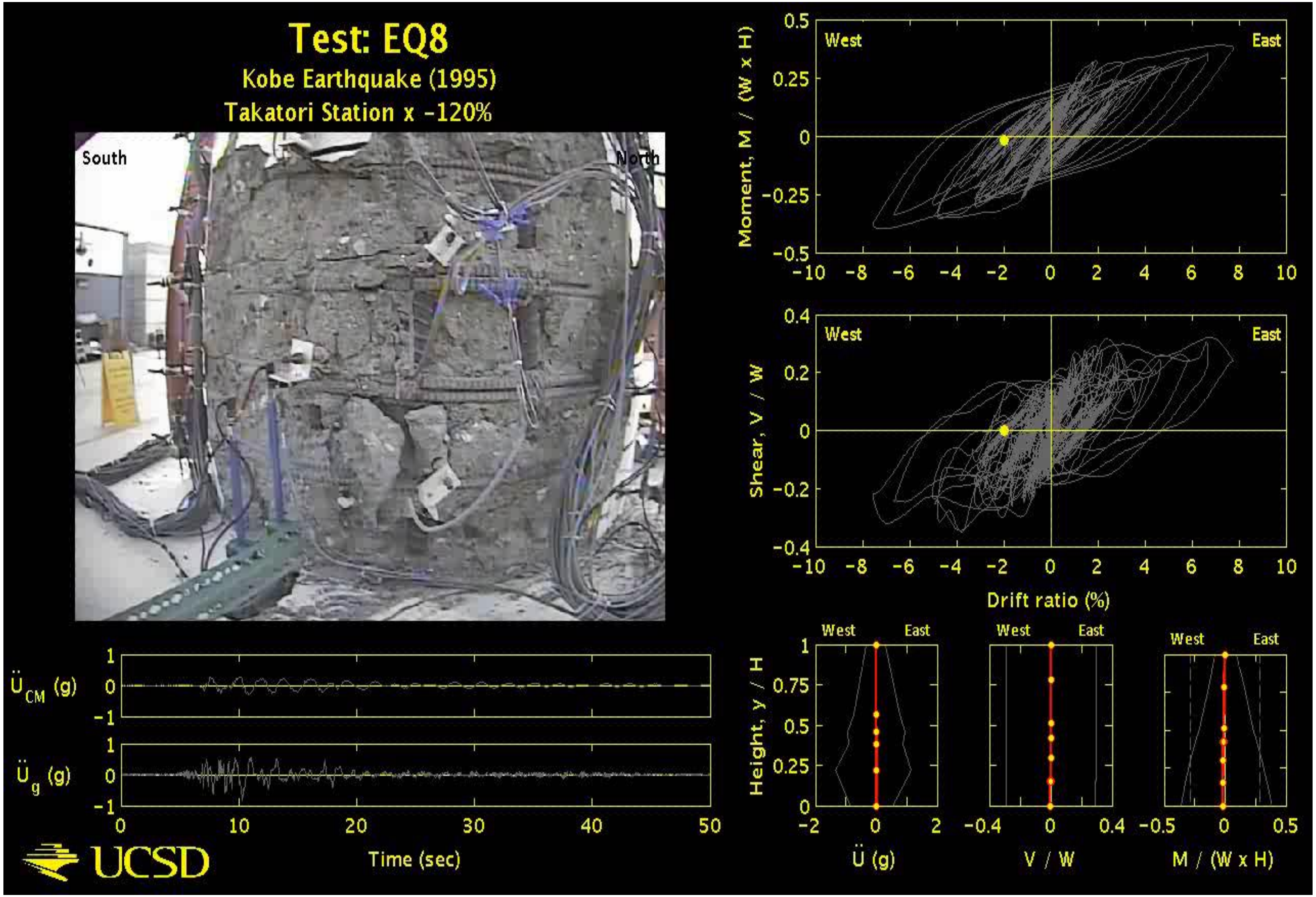


Full-Scale Structural and Nonstructural Building System Performance – Fixed Base

Large Scale Validation of Seismic Performance of Bridge Columns

PI - Prof. Jose I. Restrepo, UC San Diego





Test: EQ8
Kobe Earthquake (1995)
Takatori Station x -120%
South
North
Moment, M / (W x H)
West
East
Shear, V / W
Drift ratio (%)
Ü_CM (g)
Ü_g (g)
Time (sec)
UCSD
Height, y / H
Ü (g)
V / W
M / (W x H)

Use of LHPOST in Combination with Large Soil Boxes

Laminar soil shear box:
6.7m (L) × 3.0m (W) × 4.7m (H)

Stiff soil confinement box:
10.0m (L) × 4.6 or 5.8m (W) × 7.6m (H)

- To investigate the seismic response of soil-foundation-structural systems.
- To complement centrifuge tests in order to validate computational models.
- To study the performance of **bridge abutments**, **earth retaining walls, slope stability in hillside construction,** and **underground structures.**
- To investigate **soil liquefaction** and its effect on the seismic response of soil-foundation-structural systems.

Experimental Program to Investigate Soil-Pile Interaction in Soil Strata

PI – Prof. Ahmed Elgamal, UC San Diego

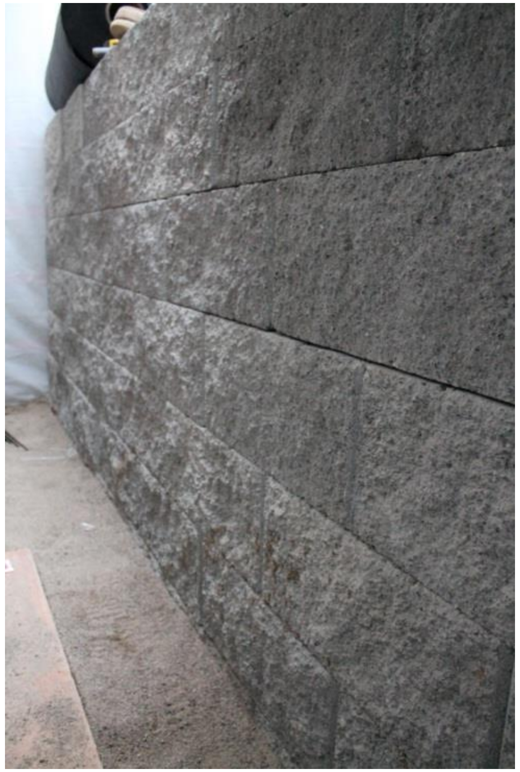
Liquefaction-Induced Lateral Spread Displacements and Soil-Pile Interaction in Multi-Layer Soil Strata

PI – Prof. Ahmed Elgamal, UC San Diego

Seismic Performance Tests of Full-Scale Retaining Walls

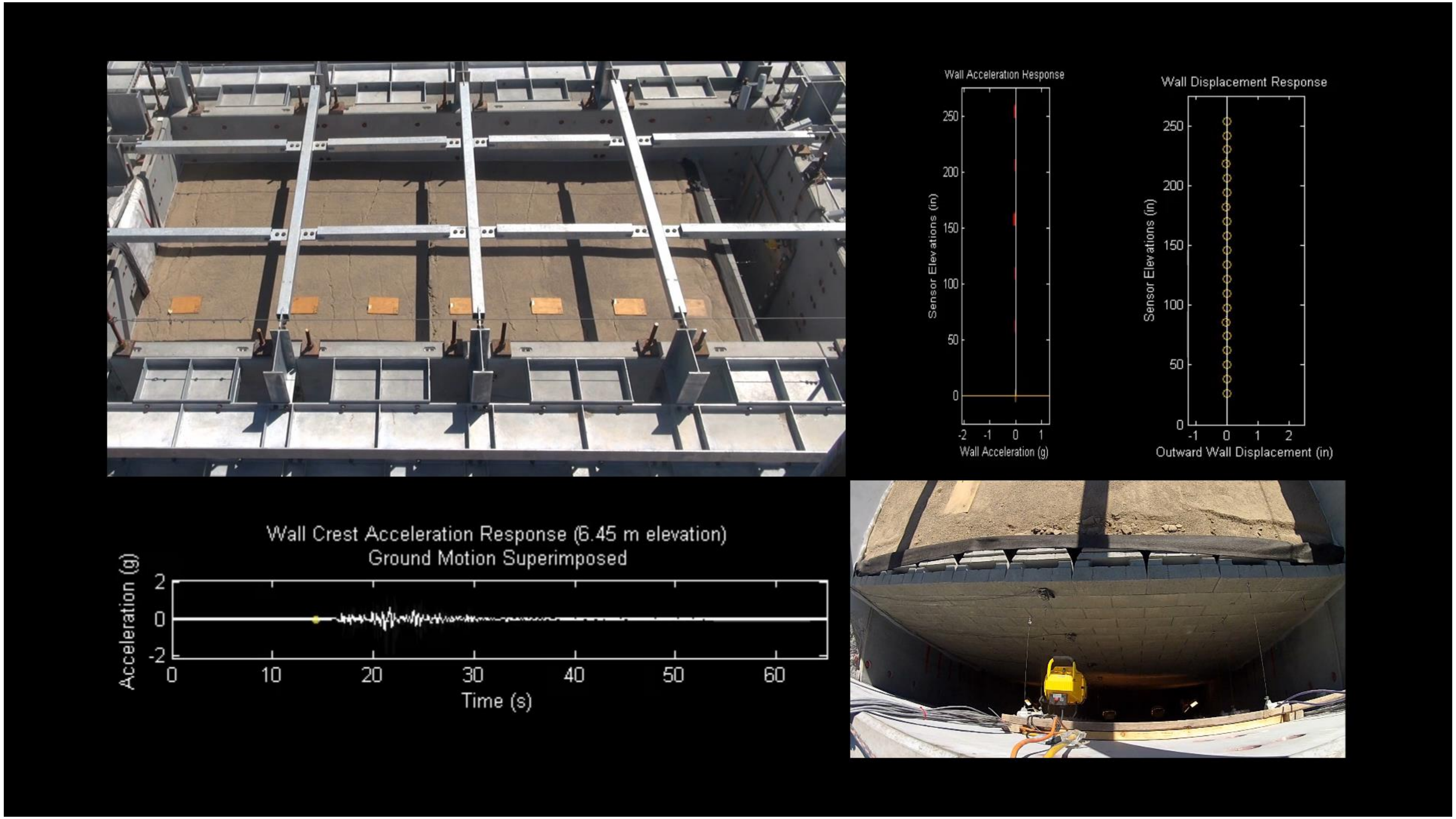
PI – Prof. Patrick Fox, UC San Diego

22 ft Above Table Elevation



Seismic Performance Tests of Full-Scale Retaining Walls

PI – Prof. Patrick Fox, UC San Diego

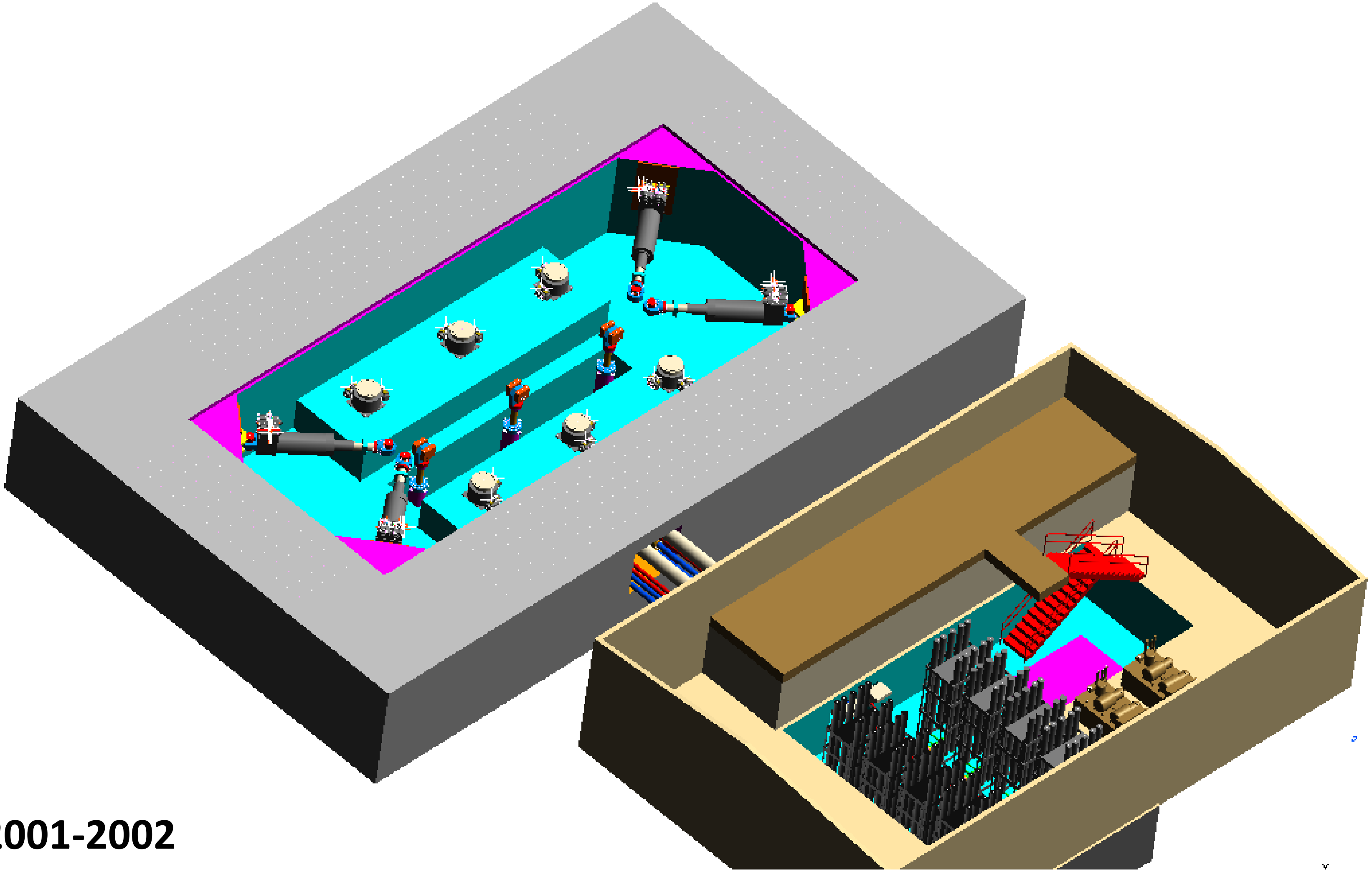


Staging Facility

Six Degree-of-Freedom (6-DOF) Upgrade of LHPOST into LHPOST6

- Upgrade NSF proposal was awarded on October 1, 2018.
- Upgrade was designed in the period October 1, 2018 – September 30, 2019.
- Upgrade was built in the period October 15, 2019 – March 30, 2022

Upgrade to 6-DOF Capability Planned from the Start



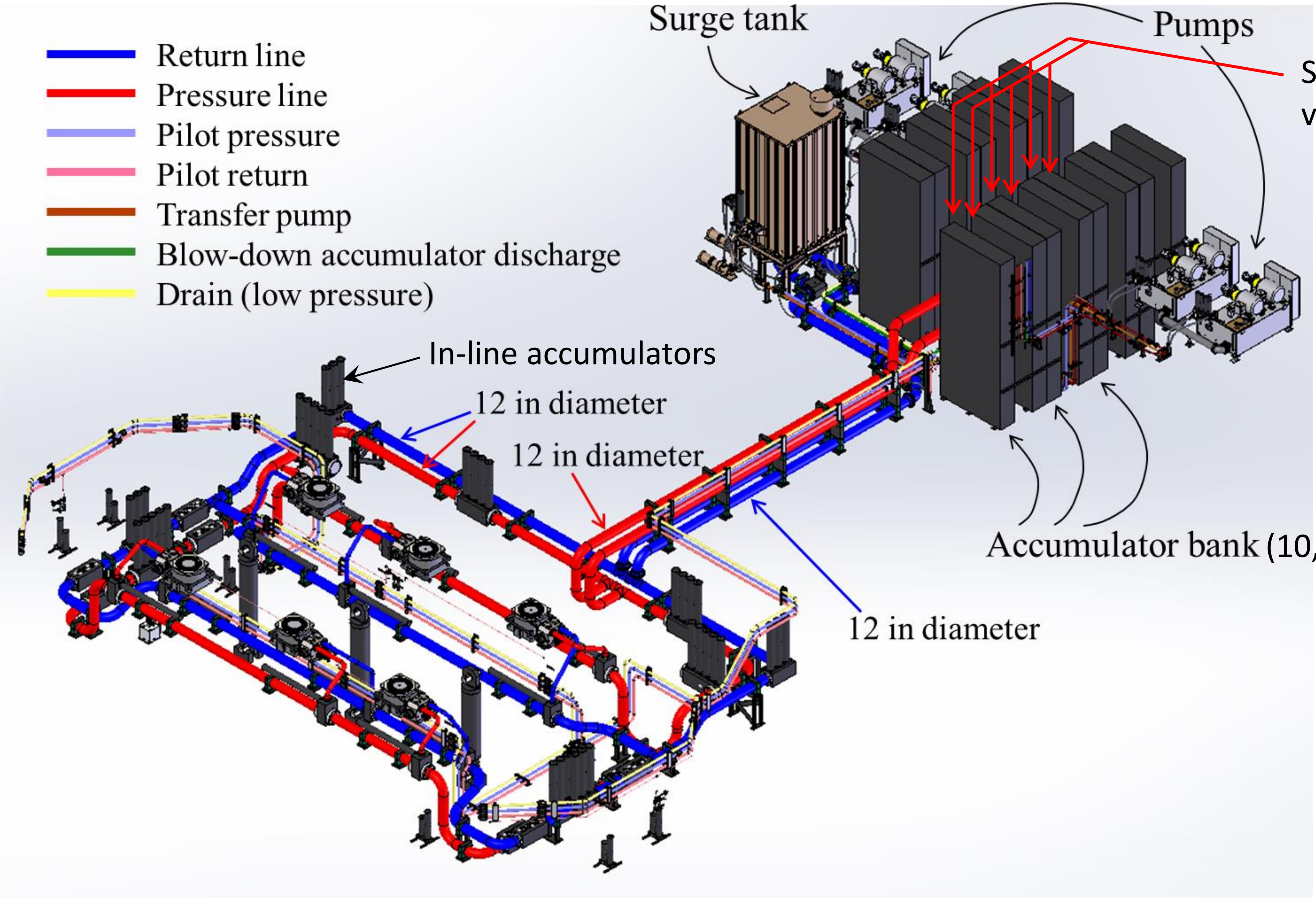
Rendering from 2001-2002

Tri-axial Strong Ground Motion Records Used to Design the 6-DOF Upgrade of the LHPOST

Event Name	Station Name	M	PGA (g)			PGV (m/s)			PGD (m)			High pass freq. (Hz)
			EW	NS	UP	EW	NS	UP	EW	NS	UP	
Tabas, 1978	Tabas, Iran	7.4	0.97	0.88	0.72	1.0	0.87	0.33	0.62	0.33	0.11	0.16
Chi-Chi, Taiwan, 1999	TCU065	7.6	0.72	0.49	0.23	0.82	0.73	0.38	0.36	0.24	0.10	0.25
Kobe, 1995	Takatori, Japan	6.9	0.62	0.67	0.28	1.21	1.23	0.16	0.40	0.30	0.04	0.125
Northridge, 1994	Rinaldi Receiving Station	6.7	0.87	0.47	0.96	1.48	0.75	0.42	0.42	0.23	0.04	0.10
Nepal, 2015	Kathmandu, Nepal	7.8	0.16	0.17	0.15	0.43	0.40	0.26	0.30	0.20	0.10	0.25
AC-156 compatible earthquake		-	1.01	0.96	0.71	1.04	1.13	0.77	0.22	0.21	0.12	0.70

Earthquake record	Peak flow rate $[m^3/min]$ ([gpm])	Total flow $[m^3]$ ([gallons])
Tabas, 1978	79.0 (20,859)	7.1 (1,872)
Chi-Chi, Taiwan, 1999	82.6 (21,815)	8.0 (2,125)
Kobe, 1995	52.5 (13,858)	5.1 (1,349)
Northridge, 1994	89.7 (23,687)	2.6 (687)
Nepal, 2015	33.8 (8,938)	8.3 (2,188)
AC-156 compatible	106.6 (28,158)	4.3 (1,130)

Hydraulic Power System of LHPOST6



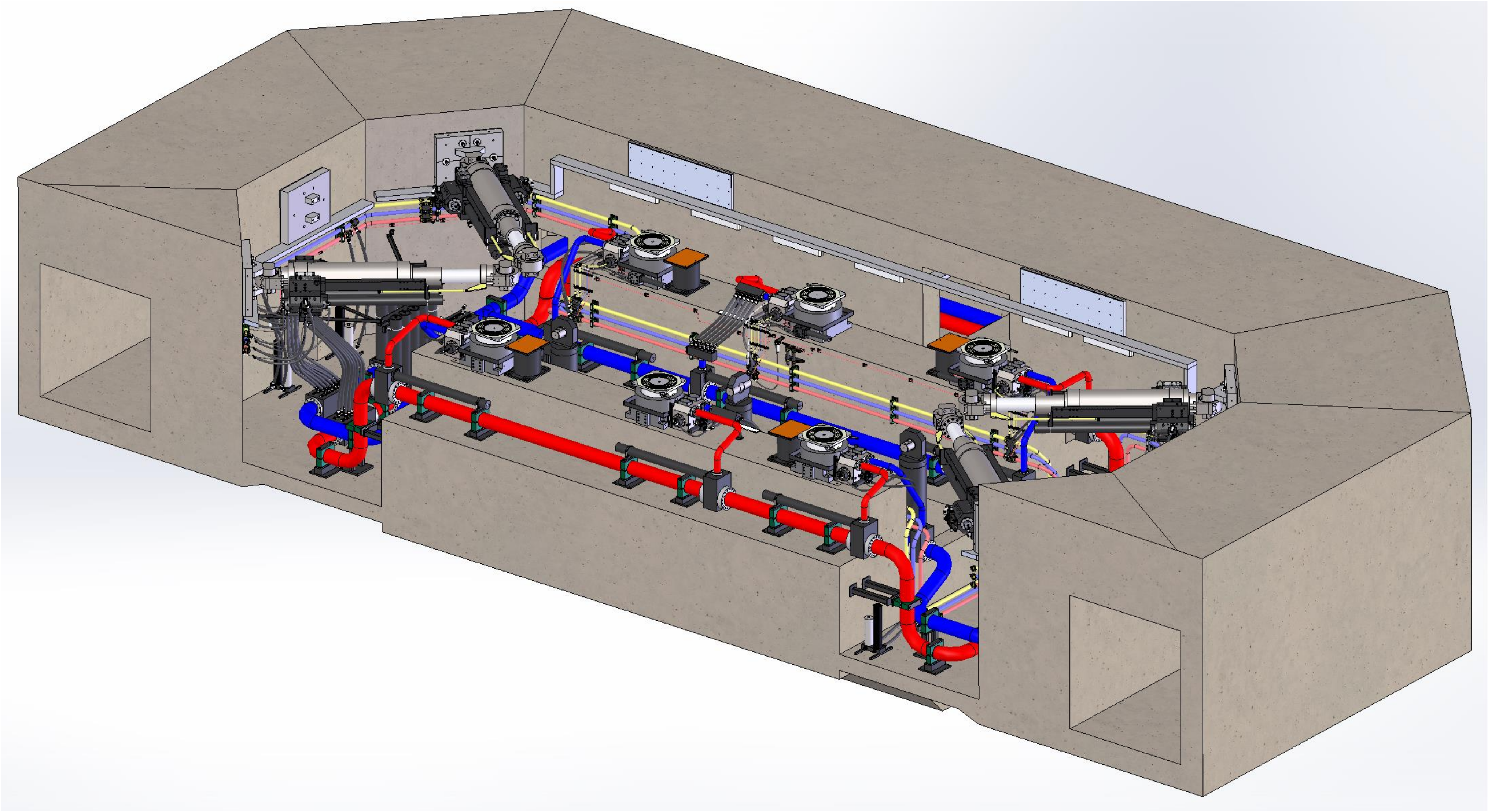
Six blow-down valves (manifolds)

(10,000 gallons)

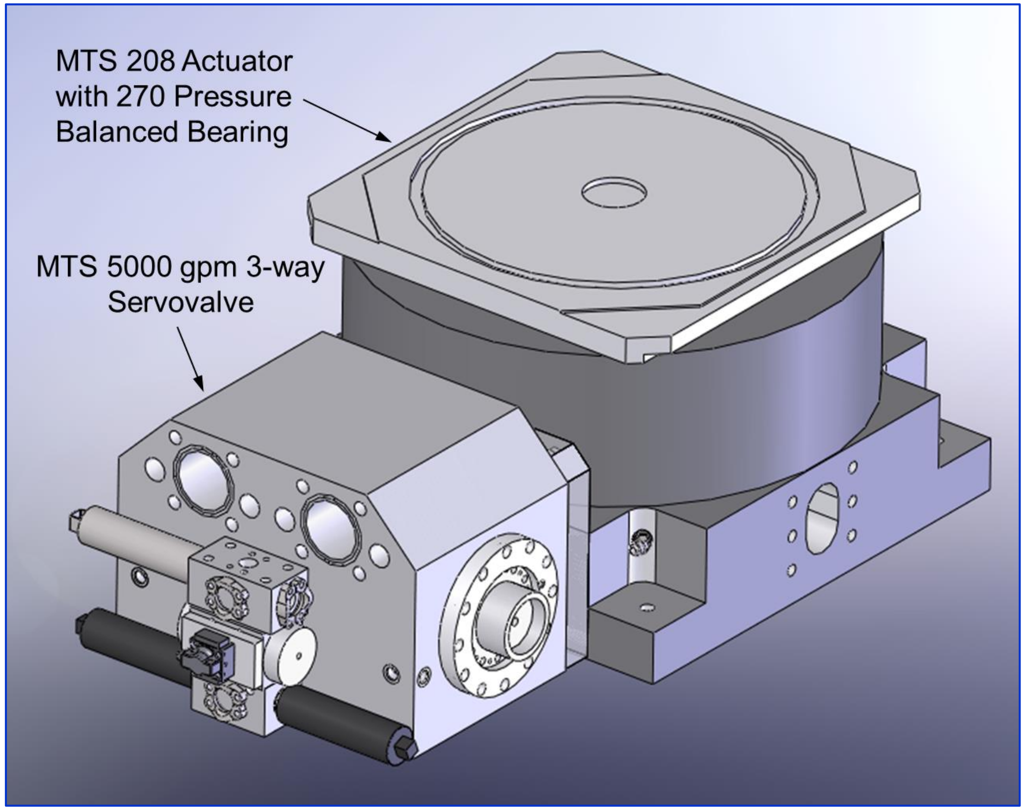
Accumulator Bank of LHPOST6

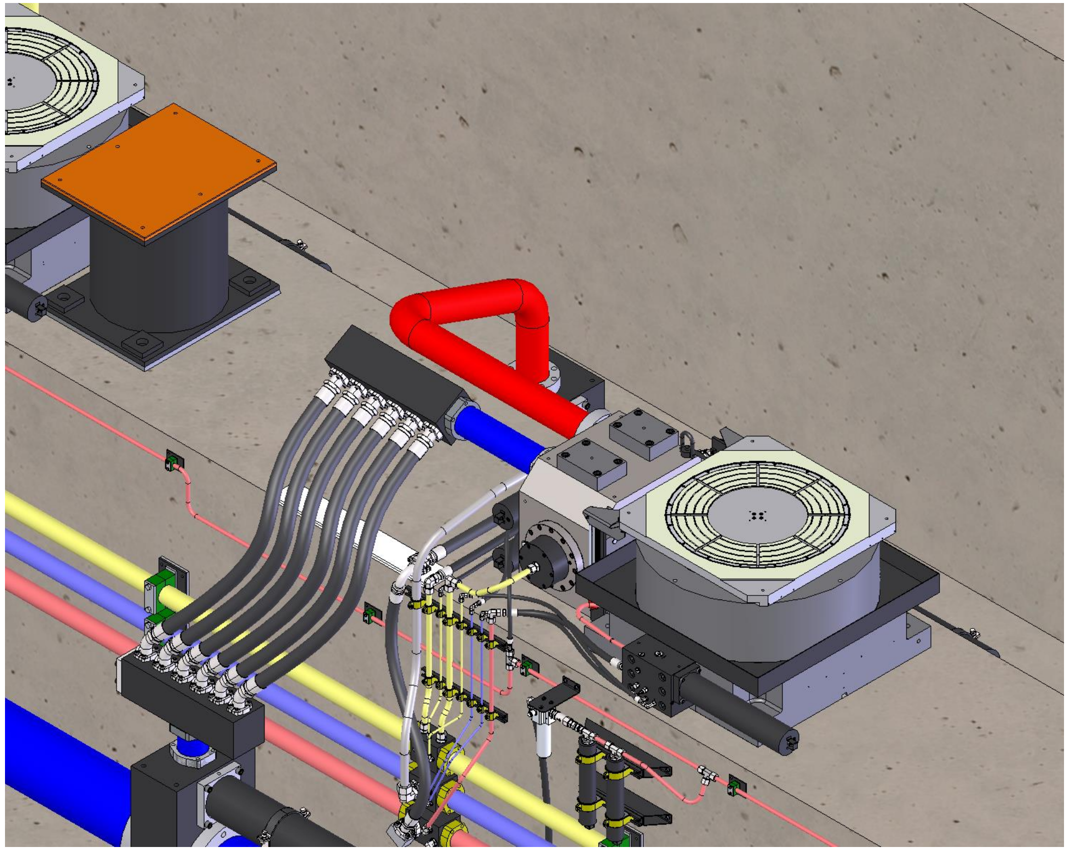
August 2020

Horizontal and Vertical Actuators of LHPOST6

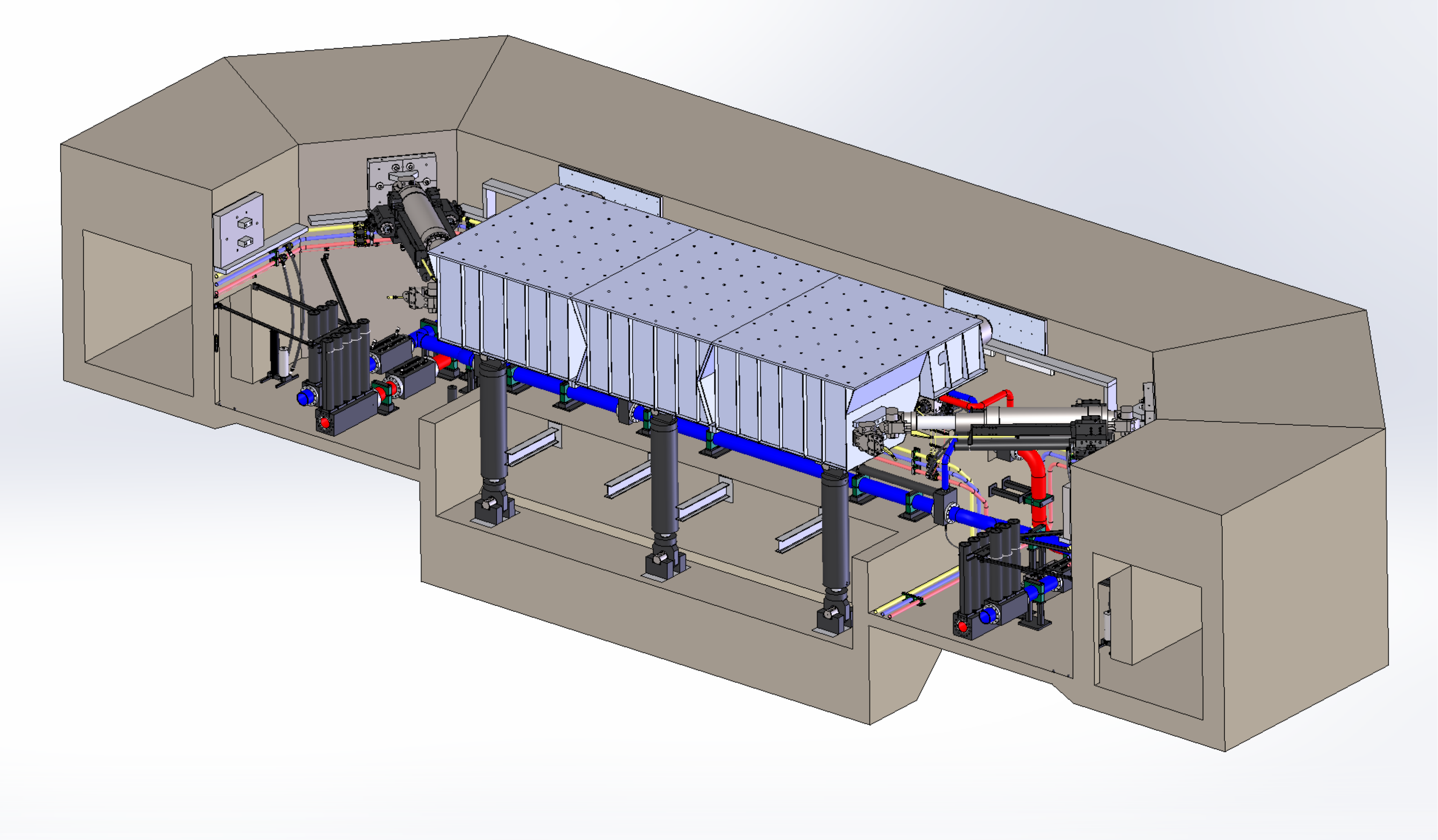


High-Flow Servovalves for Vertical Actuators

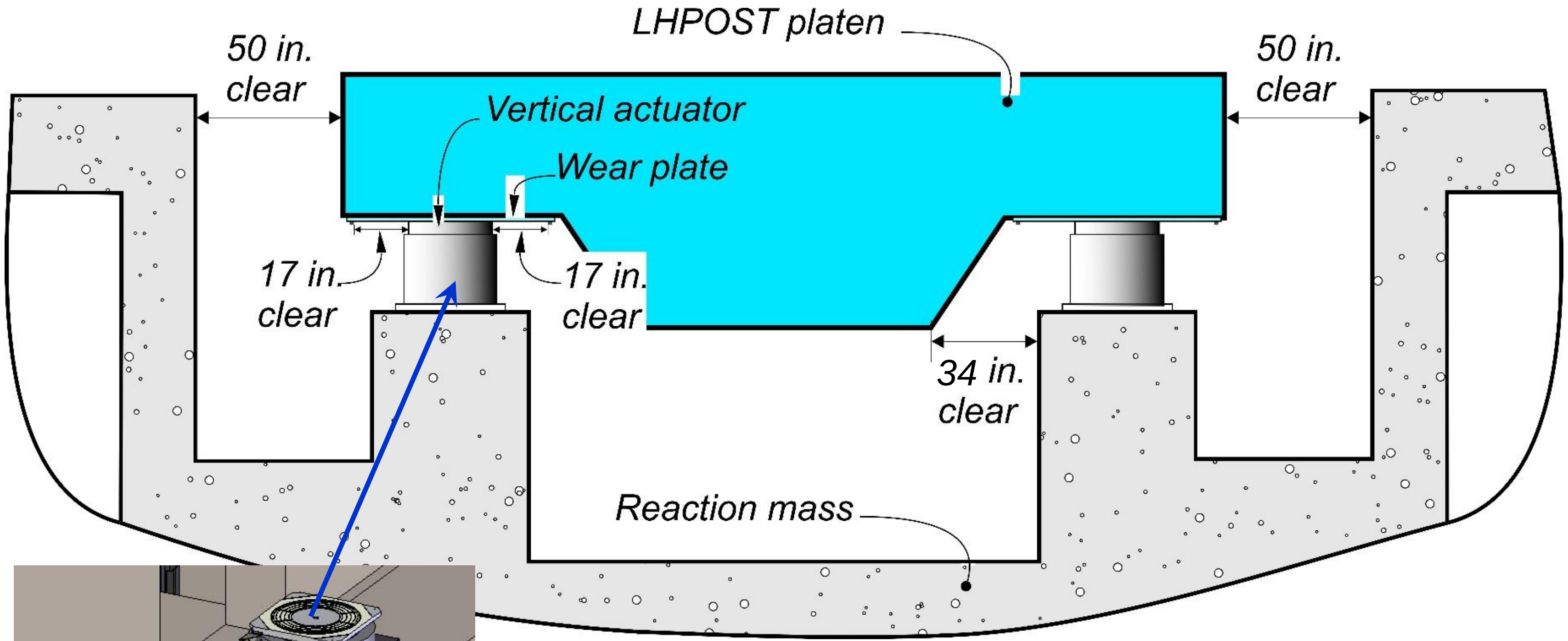


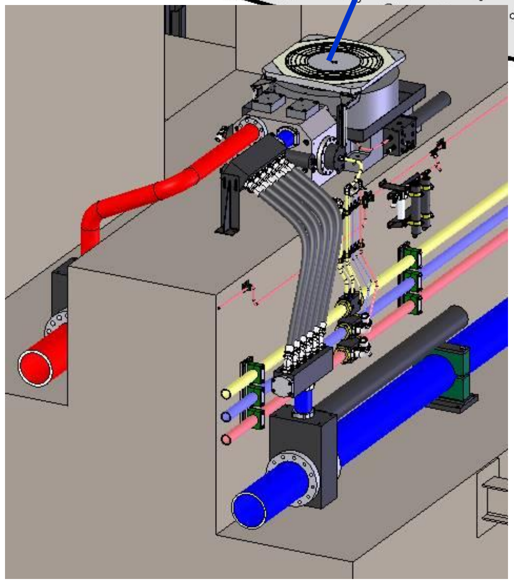


Third Nitrogen-filled Hold-down Strut



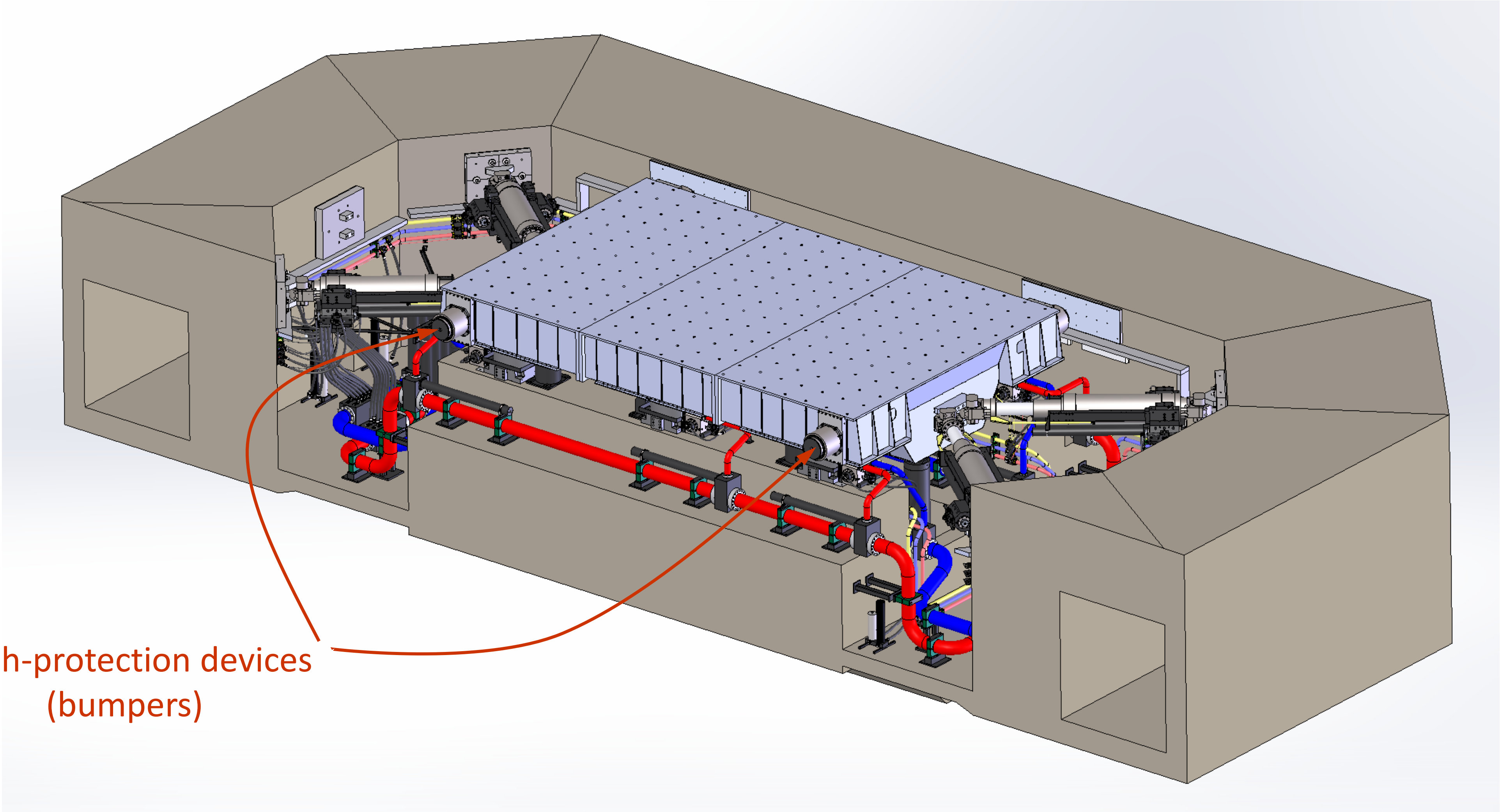
Displacement Limit in the Transverse (N-S) Direction





- Three lines of defense against potential impact:
  - Software limit detectors (interlocks)
  - Physical limit switches (LVDT’s) in a PLC control loop
  - Collision/crash protection devices (last resort)

LHPOST6



Crash-protection devices
(bumpers)

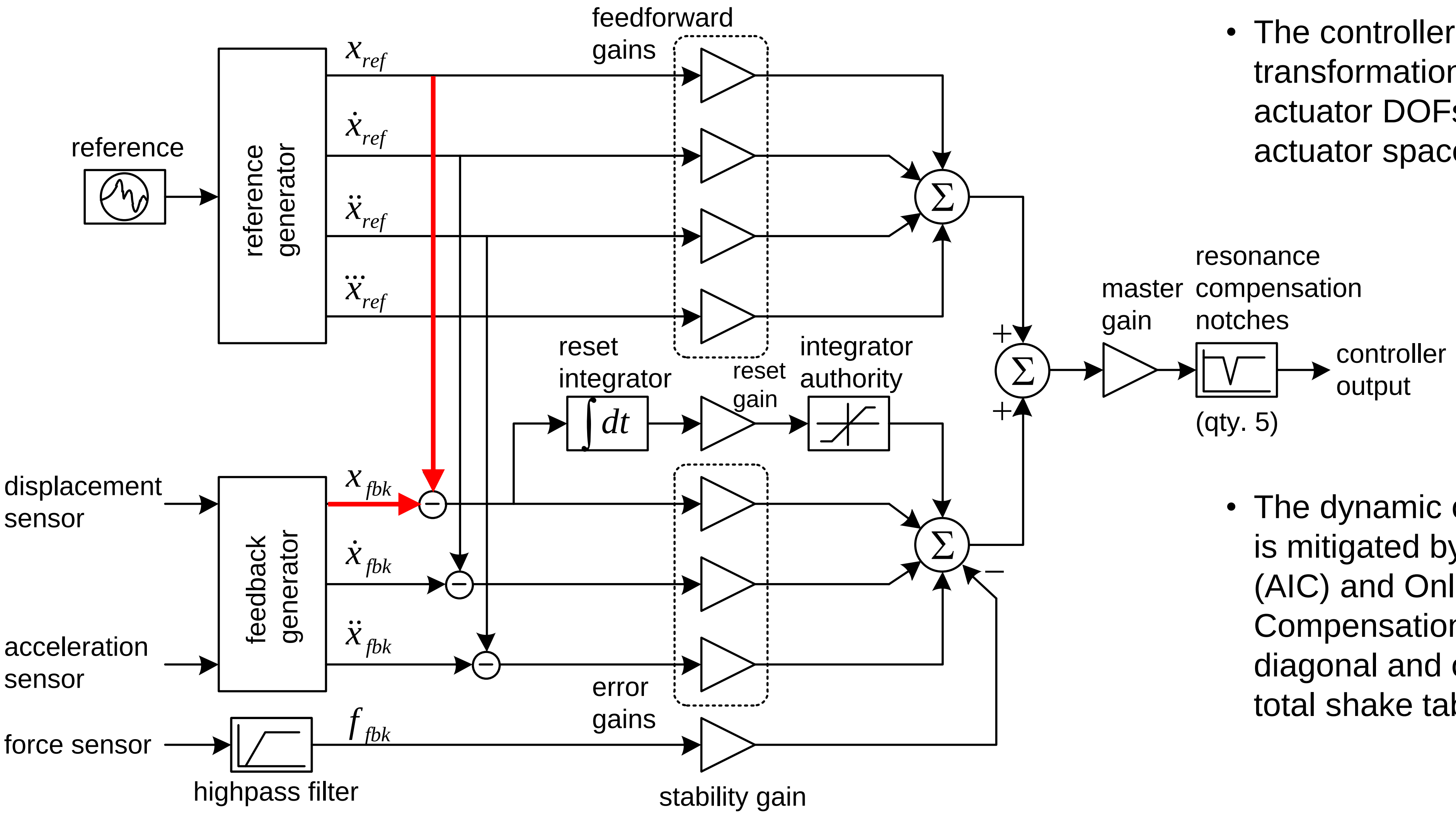
Predicted and Identified Oil Column Frequencies and Modes of LHPOST6

Predicted Oil Colum Frequency	Oil Column Mode	Identified Oil Column Frequency
f_1 = 7.40 Hz	Y/N-S/Transverse Direction	f_1 = 9.22 Hz
f_2 = 8.87 Hz	Yaw	f_2 = 11.03 Hz
f_3 = 9.33 Hz	X/E-W/Longitudinal Direction	f_3 = 11.95 Hz
f_4 = 40.66 Hz	Coupled Longitudinal (X) - Pitch (R_Y)	f_4 = 39.00 Hz
f_5 = 44.07 Hz	Z/Vertical Direction	f_5 = 40.32 Hz
f_6 = 53.03 Hz	Coupled Transverse (Y) - Roll (R_X)	f_6 = 48.34 Hz

- The predictions were obtained assuming an effective oil bulk modulus of 120,000 psi (= 60% of actual oil bulk modulus of hydraulic fluid) to account for entrained air and other sources of compliance.
- As for the 1-DOF LHPOST, the resonant peaks of the oil column modes are damped out numerically by the shake table controller using the delta-pressure feedback gains and notch filters, if necessary.

MTS 6-DOF 469D – Three-Variable Controller (TVC)

TVC = State-Variable Control + Extras



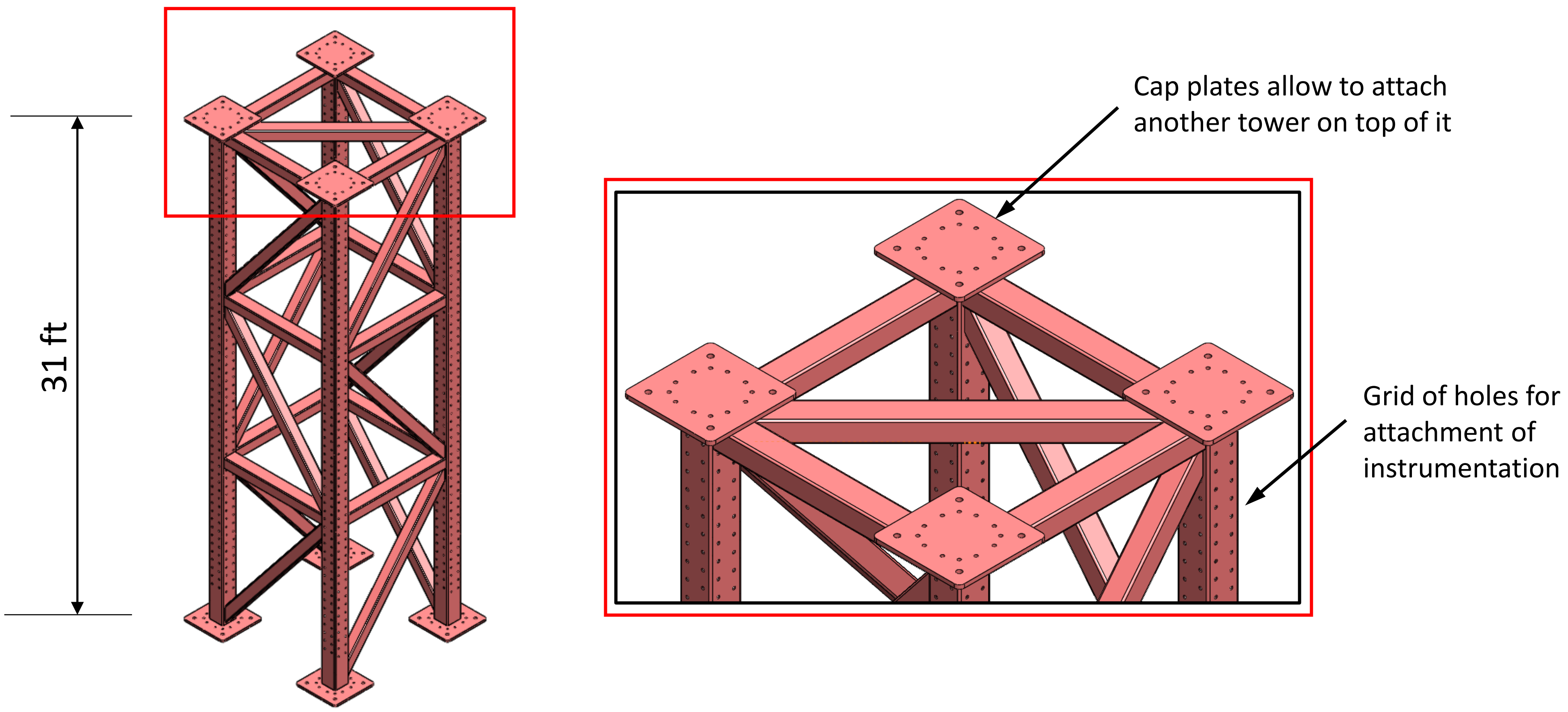
- The TVC portion of the 6-DOF 469D controller for each of the six DOFs is exactly the same as for the 1-DOF LHPOST.
- The controller uses back-and-forth transformations from Cartesian DOFs to actuator DOFs (i.e., from Cartesian space to actuator space).

Courtesy of MTS Systems Corporation

- The dynamic cross-coupling between DOFs is mitigated by Adaptive Inverse Control (AIC) and Online Iterative (OLI) Compensation, which takes care of the diagonal and off-diagonal terms of the 6×6 total shake table transfer function matrix.

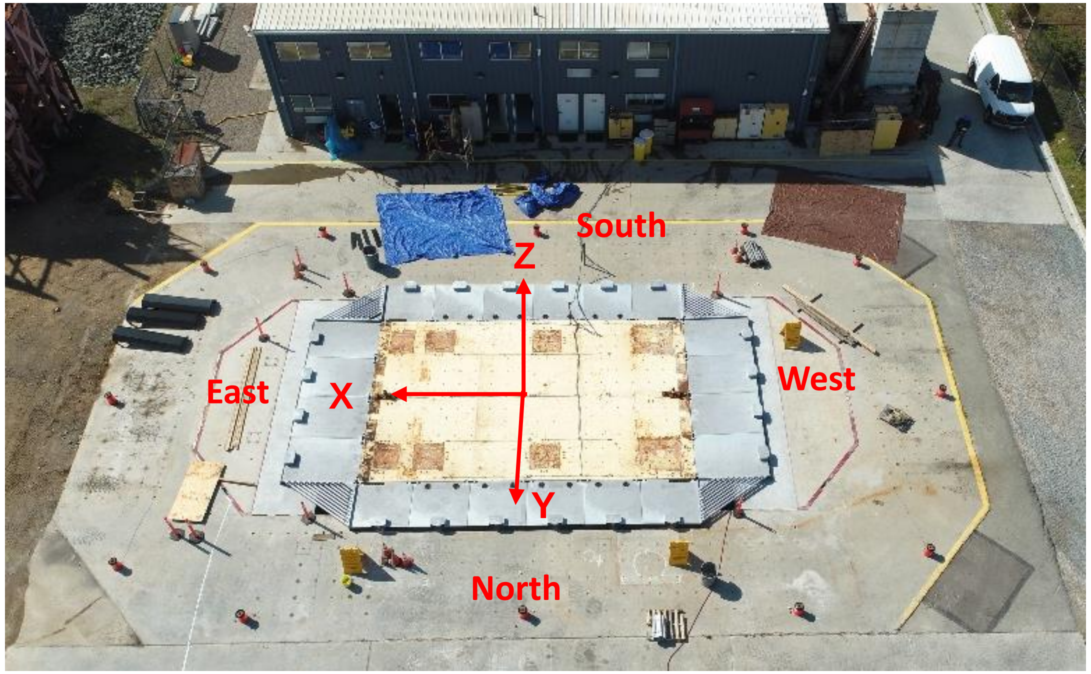
Safety Towers

- New safety towers:
  - Provide additional protection to the specimens tested on the shake table
  - Are easier to handle than previous towers



Performance of LHPOST6

LHPOST6



Performance Characteristics of LHPOST6

Uniaxial performance characteristics of the LHPOST6
Sinusoidal motions - Bare table condition - Centered rigid payload of 4.9 MN (1,100 kips)

Platen size	12.2 m × 7.6 m (40 ft × 25 ft)					
Frequency Bandwidth	0 – 33 Hz					
Vertical Payload Capacity	20 MN (4,500 kip)					
	Sinusoidal motions - Bare table condition			Sinusoidal motions - Centered rigid payload of 4.9 MN (1,100 kips)		
	Horizontal X (E-W)	Horizontal Y (N-S)	Vertical Z (-)	Horizontal X (E-W)	Horizontal Y (N-S)	Vertical Z (-)
Peak Translational Displacement	±0.89 m (±35 in)	±0.38 m (±15 in)	±0.127 m (±5 in)	±0.89 m (±35 in)	±0.38 m (±15 in)	±0.127 m (±5 in)
Peak Translational Velocity	3.0 m/sec (118 in/sec)	2.0 m/sec (80 in/sec)	0.45 m/sec (17 in/sec)	3.0 m/sec (118 in/sec)	2.0 m/sec (80 in/sec)	0.55 m/sec (21 in/sec)
Peak Translational Acceleration	(5.8 g)(1) 3.7 g (2)	(4.7 g)(1) 1.85 g (2)	-3.4 g +31.1 g (1) +11.9 g (3)	(1.6 g)(1) 1.0 g (2)	(1.25 g)(1) 0.50 g (2)	-1.64 g +7.5 g (1) +2.5 g (2)
Peak Translational Force	10.6 MN (1) (2,380 kip)(1) 6.8 MN (2) (1,530 kip)(2)	8.38 MN (1) (1,890 kip)(1) 3.4 MN (2) (765 kip)(2)	-4.3 MN (4) +57.0 MN (5) (+12,800 kip)(5) +22.9 MN (6) (+5,150 kip)(6)	10.6 MN (1) (2,380 kip)(1) 6.8 MN (2) (1,530 kip)(2)	8.38 MN (1) (1,890 kip)(1) 3.4 MN (2) (765 kip)(2)	-4.3 MN (4) +57.0 MN (5) (+12,800 kip)(5) +22.9 MN (6) (+5,150 kip)(6)
Peak Rotation	2.22 deg (7)	1.45 deg (7)	3.8 deg	2.22 deg (7)	1.45 deg (7)	3.8 deg
Overturning Moment Capacity	32.0 MN-m (23,600 kip-ft)	35.0 MN-m (25,800 kip-ft)		45.1 MN-m (33,200 kip-ft)	50.0 MN-m (36,900 kip-ft)	

(1) Peak acceleration controlled by the actuator force capacities in the control zero-position of the table.

(2) Acceleration limit controlled by the reaction mass until further studies.

(3) Acceleration limit controlled by the design strength of the steel honeycomb platen.

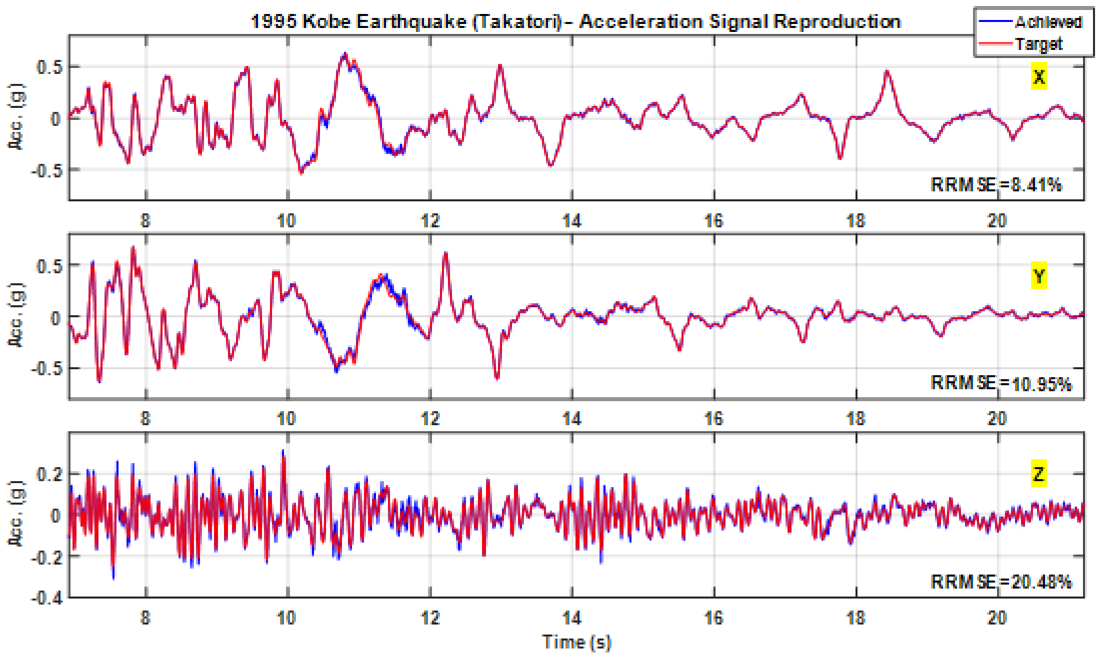
(4) Assuming a pressure of 125 psi in the chamber of each vertical actuator and accounting for the hold-down forces in the control zero-position of the table.

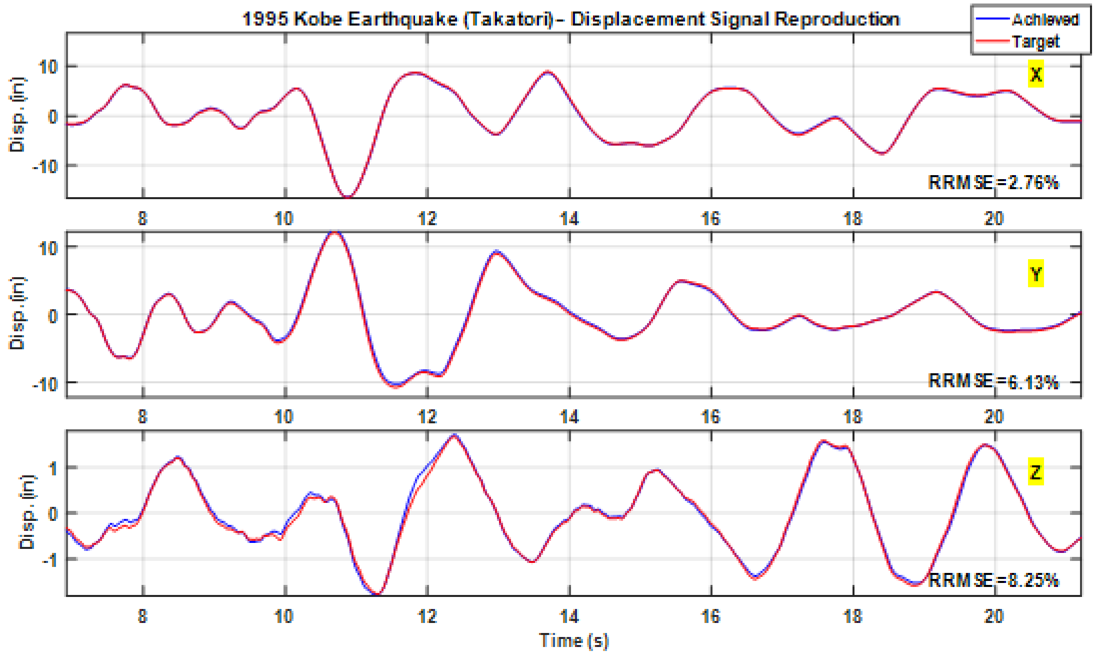
(5) Peak force controlled by the vertical actuator force capacities and accounting for the hold-down forces in the control zero-position of the table.

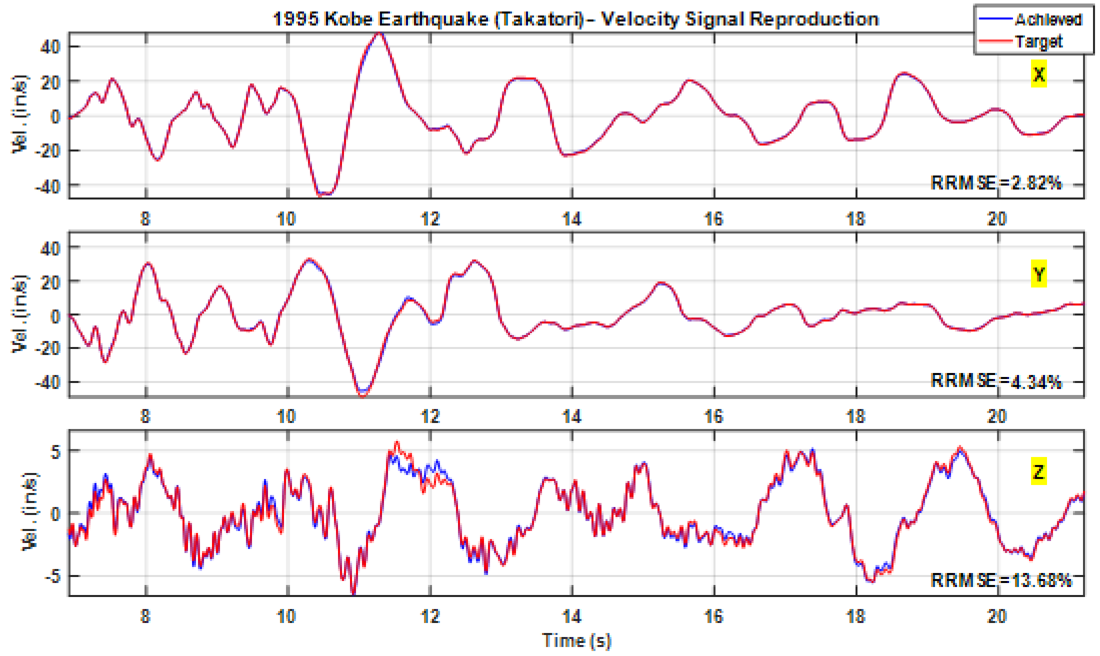
(6) Force limit controlled by the design strength of the steel honeycomb platen and accounting for the hold-down forces in the zero control position of the table.

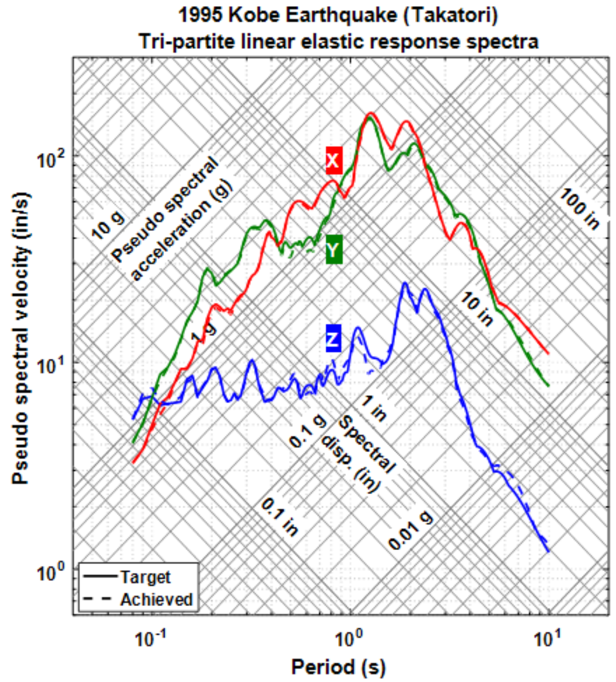
(7) Due to kinematics of the piston seals of the vertical actuators.

Target vs. Achieved Tri-Axial Ground Motion - 1995 M6.9 Kobe, Japan, Takatori Station









1978, M7.4 Tabas, Iran, Tri-Axial Ground Motion

AC-156 Compatible Earthquake, Tri-Axial Ground Motion

Synthetic Six-Axial Ground Motion

1994 Northridge Earthquake (Rinaldi Station) – Tri-axial – 100%

Shared-use Modular Test Bed Building (MTB2) Project

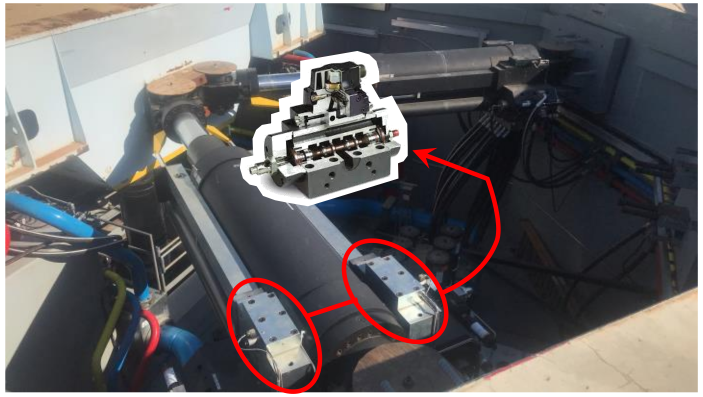
Tara Hutchinson and Gilberto Mosqueda, UC San Diego
Chris Pantelides, The University of Utah

Mechanics-Based Virtual Model (Digital Twin) of the LHPOST6

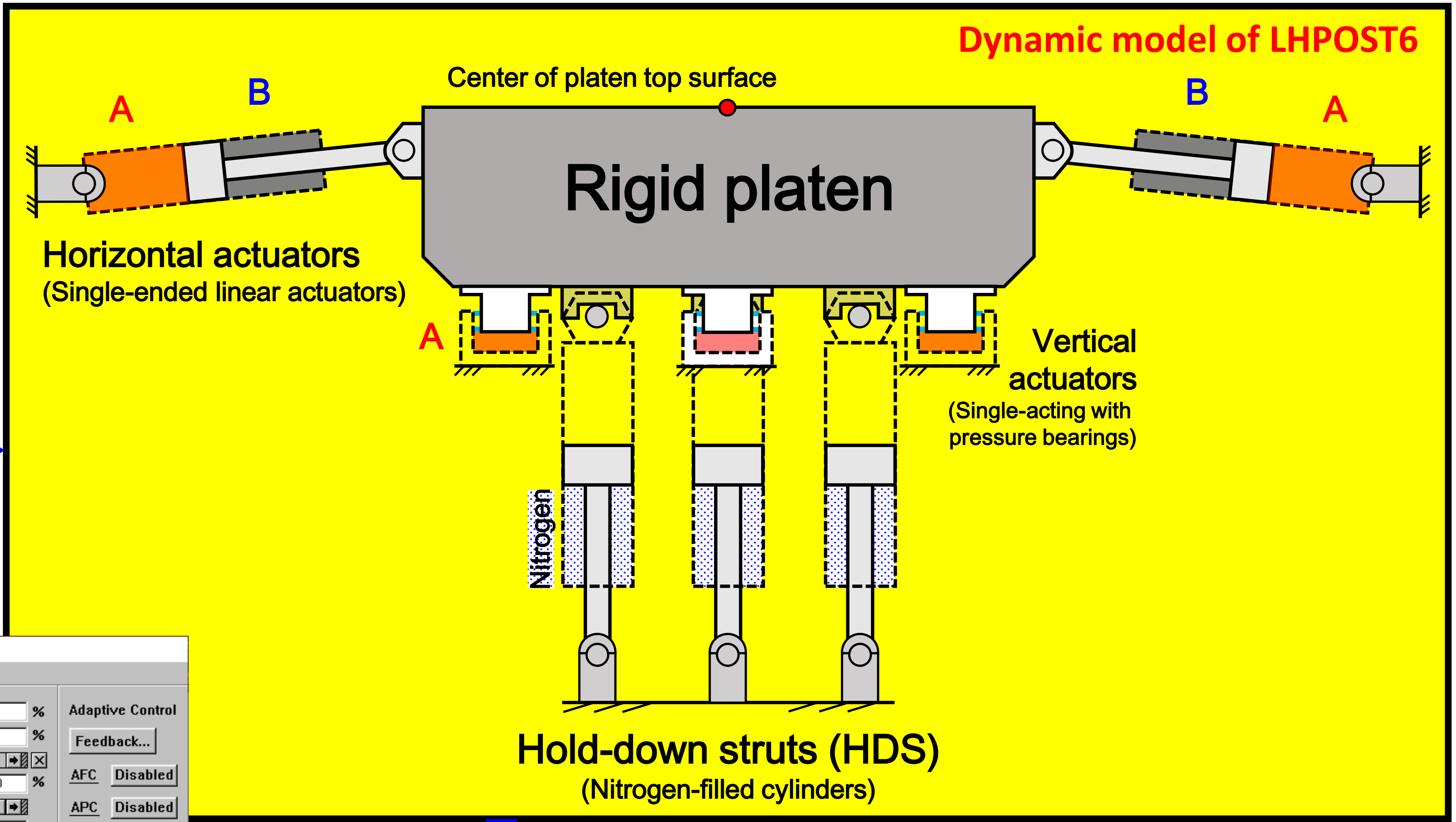
Purposes of virtual model of the LHPOST6:

- Pre-test simulation (“dry-runs”) of shake table tests, i.e., evaluate signal tracking performance of LHPOST6 prior to construction of the test specimen.
- Off-line tuning or pre-tuning of shake table controller based on the test specimen characteristics.
- Investigate control-table-specimen interaction (i.e., interpreting the results of shake table experiments).
- Safe offline training of shake table operator (i.e., shake table simulator).
- Development of next-generation shake table controllers.
- Real-time hybrid shake table testing.

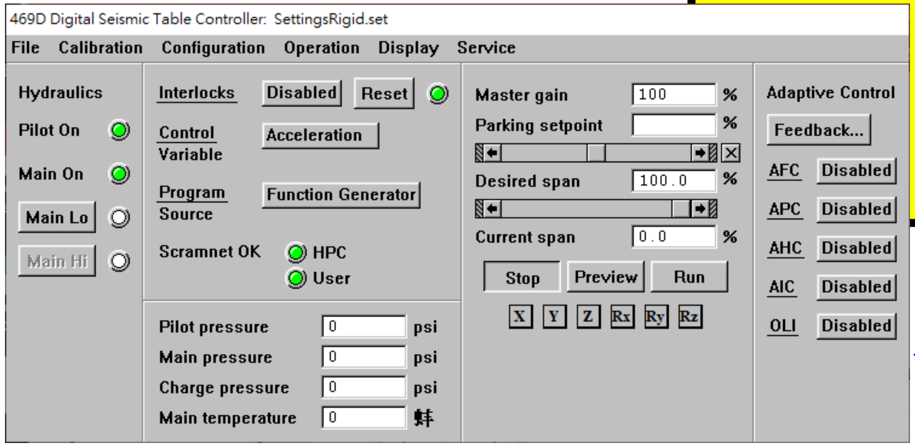
Digital Twin of the LHPOST6



Servovalve commands



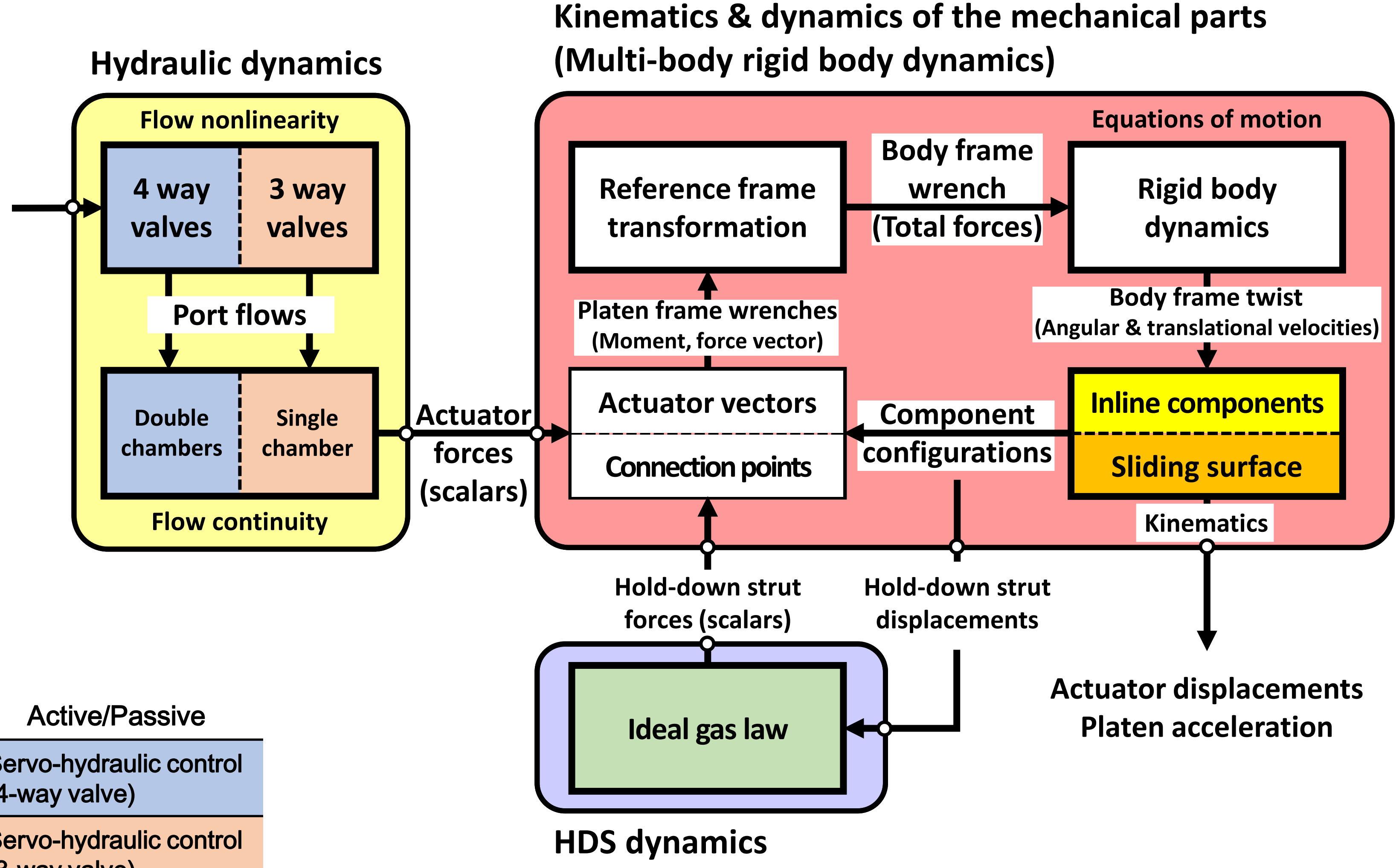
MTS 469D (6-DOF controller)

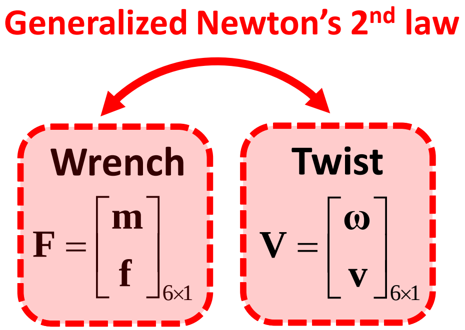


Platen motion (displacement and acceleration feedback)

Block Diagram of the Digital Twin of the LHPOST6

MATLAB + SIMULINK®





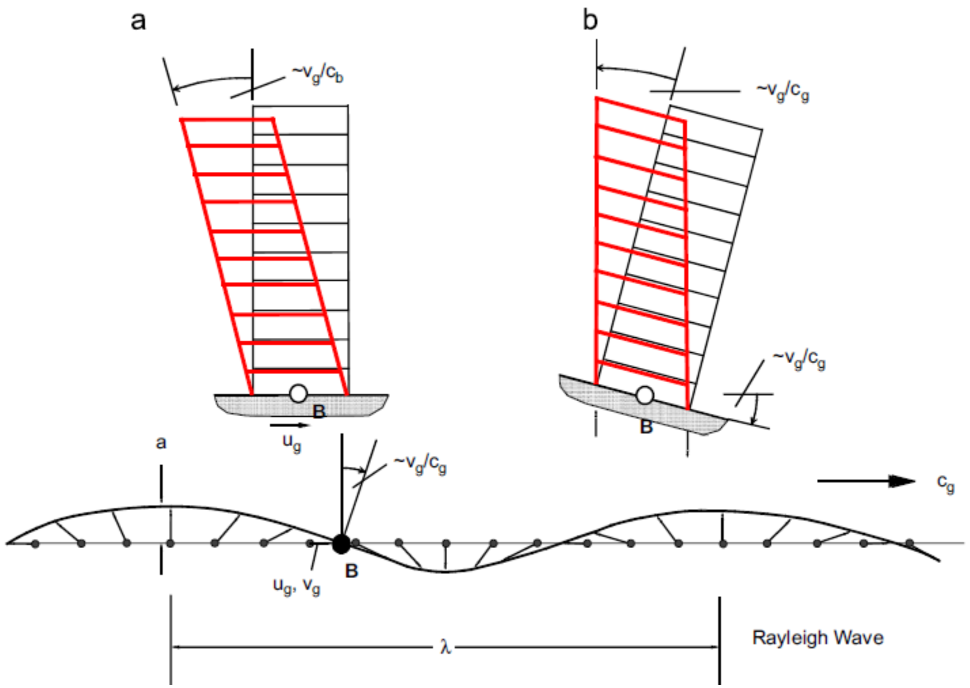
$$\mathbf{F} = \begin{bmatrix} \mathbf{m} \\ \mathbf{f} \end{bmatrix}_{6\times1} \qquad \mathbf{V} = \begin{bmatrix} \boldsymbol{\omega} \\ \mathbf{v} \end{bmatrix}_{6\times1}$$

	Kinematics	Active/Passive
Horizontal Actuators	Linear actuator	Servo-hydraulic control (4-way valve)
Vertical Actuators	Sliding surface	Servo-hydraulic control (3-way valve)
Hold-down Struts	Linear actuator	Nitrogen pre-charged (passive component)

New Research Opportunities Made Possible by the LHPOST6

New Research Opportunities Made Possible by the LHPOST6

- Investigate the combined effect of realistic near-field translational and rotational earthquake ground motions applied as dynamic excitation to full 3D and large/full-scale structural, geotechnical, or soil-foundation-structural systems, including the effects of SSI (both kinematic and inertial), nonlinear soil and structural behavior, soil liquefaction and seismic compression.



Geometric interpretation of how horizontal translation and rocking can contribute to the total drift in a simple building during passage of a Rayleigh wave [Trifunac, 2009]

New Research Opportunities Made Possible by the LHPOST6

- **Understanding inherent damping in structures to settle the issue of which is the best damping model to be used in linear and nonlinear time history analyses:**
  - Shake table experiments with multi-directional seismic base excitation on large-scale building specimens with and without non-structural components and systems and large-scale bridge sub-structures (e.g., bridge bents) will guide in the selection of appropriate inherent damping models.

- **Experimental study of dynamic soil-foundation-structure interaction and geotechnical systems:**
  - Kinematic interaction of the foundation with the soil (in the absence of the superstructure).
  - Inertial interaction (➔ additional rocking and torsional components of motion of the foundation).
  - Three general types of experimental SSI studies become possible:
    - Verification studies under multi-axial excitation (i.e., apply numerically simulated total foundation motion to the shake table platen).
    - Large soil box studies under multi-axial excitation.
    - Hybrid tests.
  - Reinforced soil systems, retaining walls, tunnels, slopes and embankments, soil improvement techniques.
  - Geotechnical issues that cannot be studied in laboratory-scale experiments, e.g., lateral spread in layered soils, liquefaction of gravelly soils, seismic response of alternative backfill materials such as tire-derived aggregates, seismic settlements of saturated soils, seismic compression of unsaturated soils.

New Research Opportunities Made Possible by the LHPOST6

- **Seismic safety of unreinforced masonry buildings:**
  - URM walls subjected to uni-axial in-plane forces tend to exhibit a much better performance than under bi-axial seismic loading conditions (out-of-plane collapse).
  - Vertical ground acceleration could also play an important role on the strength capacity (arching mechanism) and stability of URM walls.
- **Seismic performance of reinforced concrete and reinforced masonry wall structures:**
  - Design provisions for RC and reinforced masonry shear walls are primarily based on in-plane horizontal loading tests of wall components.
  - Effects of simultaneous bi-horizontal and vertical ground excitation could play a significant role on the seismic performance of a building with RC or reinforced masonry walls.
- **Structural Concrete and Precast Concrete Systems:**
  - Research is needed on innovative, seismic-resilient concrete systems under multi-axial seismic base excitation, specifically to validate earthquake protective systems under more realistic conditions and improve modeling and analysis capabilities for component and system behavior.
  - Use of high-strength (or ultra-high performance) materials (reinforcing bars and concrete) and advanced materials (e.g., fiber-reinforced concrete).
  - Seismic performance of commercial tilt-up buildings (which behaved poorly during the 1994 Northridge Earthquake).
- **Structural Steel Systems:**
  - Development of innovative low damage seismic resistant steel structures, modeling, and analysis of floor diaphragms, chords, and seismic collectors.

New Research Opportunities Made Possible by the LHPOST6

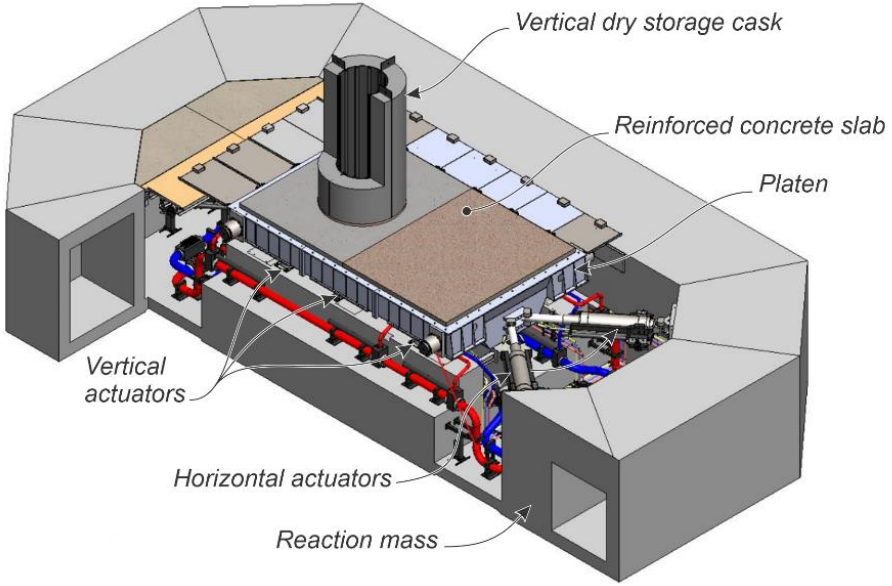
- **Non-structural components and systems (NSCs):**
  - Full-scale shake table tests are needed to advance the development of a reliable, unified design methodology accounting for multi-directional earthquake excitation.

- **Advanced and/or innovative earthquake protective systems (passive, semi-active):**
  - Low-damage structural earthquake protective systems (e.g., base isolation, dampers, buckling-restrained braces, rocking foundations and systems, self-centering systems, inertial force-limiting floor anchorage systems, new materials) for mass timber, concrete and steel structures.
  - Investigate the response behavior of these high-performance systems (with complex kinematics) under multi-directional earthquake input excitation.
  - Testing of a wide range of promising/innovative passive and semi-active seismic response modification devices in large/full-scale systems for ultimate validation and acceptance in real-world structural seismic design.

- **Building Structures:**
  - Investigate the interactions between the lateral and gravity force resisting systems and non-structural systems.
  - Validation (at large-scale) of innovative seismic retrofit systems/strategies for older non-ductile non-code compliant (wood, masonry, concrete, and steel) building structures.

New Research Opportunities Made Possible by the LHPOST6

- **Energy/power structures:**
  - Infrastructure supporting renewable energy sources:
    - Wind turbine farms, including the effects of SSI on the dynamic response of these tall and slender structural systems.
    - Solar arrays.
    - Hydroelectric concrete dams.
    - Electrical power network structures (e.g., electrical substations, large transformers, transmission poles/lines).
    - Seismic performance of nuclear structures, systems, and components (SSCs) including dry storage casks of spent nuclear fuel.
    - Experimental seismic tests of nuclear SSCs have been performed for several decades, but often facing limitations on payload capacity and/or multi-directional seismic input.



New Research Opportunities Made Possible by the LHPOST6

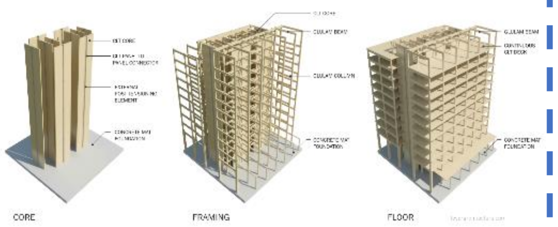
- **Bridge structures:**
  - A great challenge in the seismic design of slender columns that are part of a complex highway interchange system is to properly evaluate its response under the combined effects of vertical and bi-directional horizontal excitations.
  - Accelerated bridge construction.
  - 3D behavior of precast segmental bridge superstructures for accelerated bridge construction.
  - Bridges with hybrid sliding-rocking columns.
  - Use of smart materials in bridges.
  - High-performance steel highway bridge systems.
  - Multi-directional dynamic experimental evaluation of bridge superstructure-abutment-substructure interactions for configurations commonly employed in the Central United States.
- **Structural Health Monitoring:**
  - The high-quality datasets collected from the landmark experiments performed on the LHPOST6 are invaluable for evaluating vibration-based condition/damage assessment methodologies and resolving the remaining obstacles preventing reliable real-world implementation of such methodologies.
- **Enable Research Needs for the Full-Realization of Performance-based and Resilient-based Design:**
  - The LHPOST6 facility will provide landmark experimental data at the subsystem and system levels critical to: (1) the development of reliable fragility functions, and (2) the development, calibration and validation of high-fidelity simulation models that are able to predict the nonlinear behavior of structural materials, components, and systems under different hazard scenarios.

NHERI TallWood Project

Project duration: 2016~2023

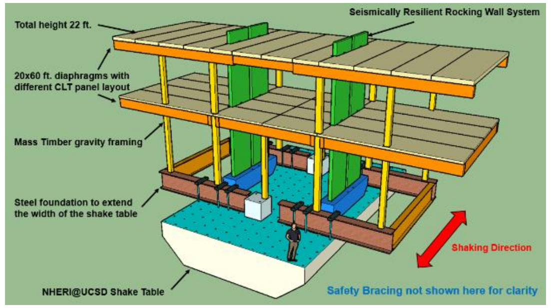
Developing Resilience-based Seismic Design Method for Tall Wood buildings

Concept: What can sell?

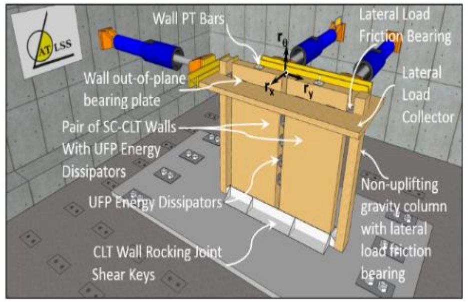


Define Tall Wood Archetypes

Appetizer: Investigative testing



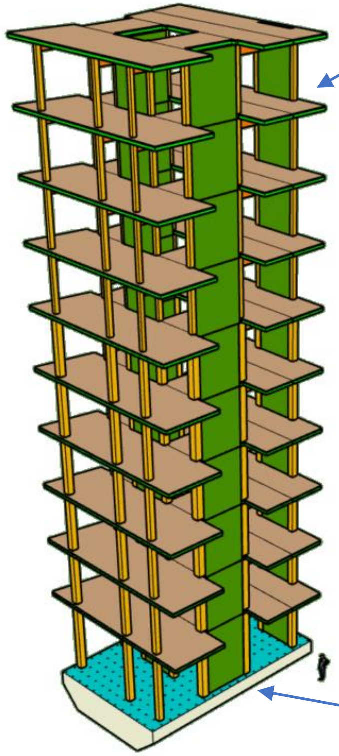
Two-story test at NHERI@UCSD 2017 Summer

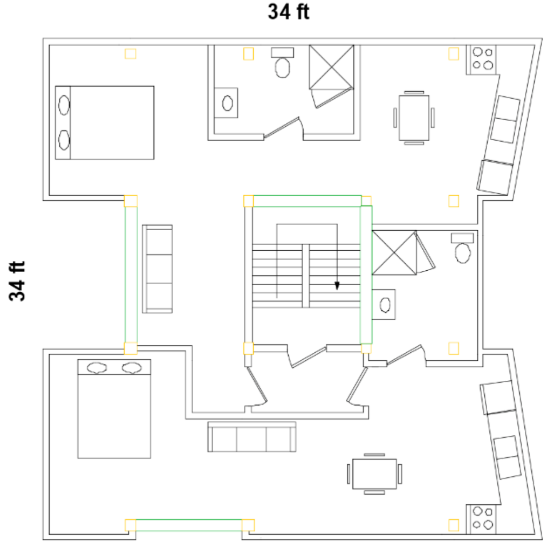


Assembly test at NHERI@Lehigh 2019-2020

Main Course: Full-scale 10-story validation

Mass timber system



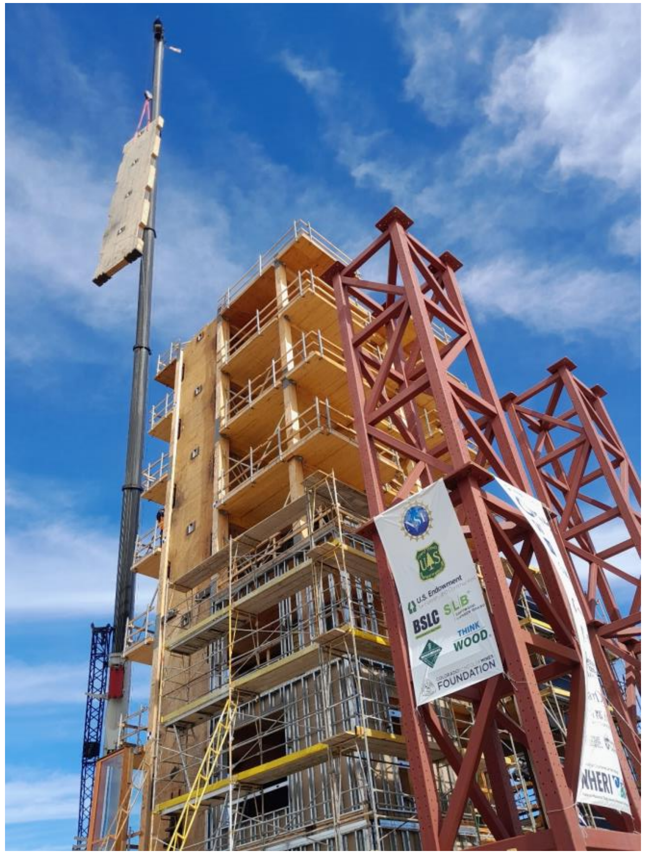


UCSD Shake Table

Seismic R & D

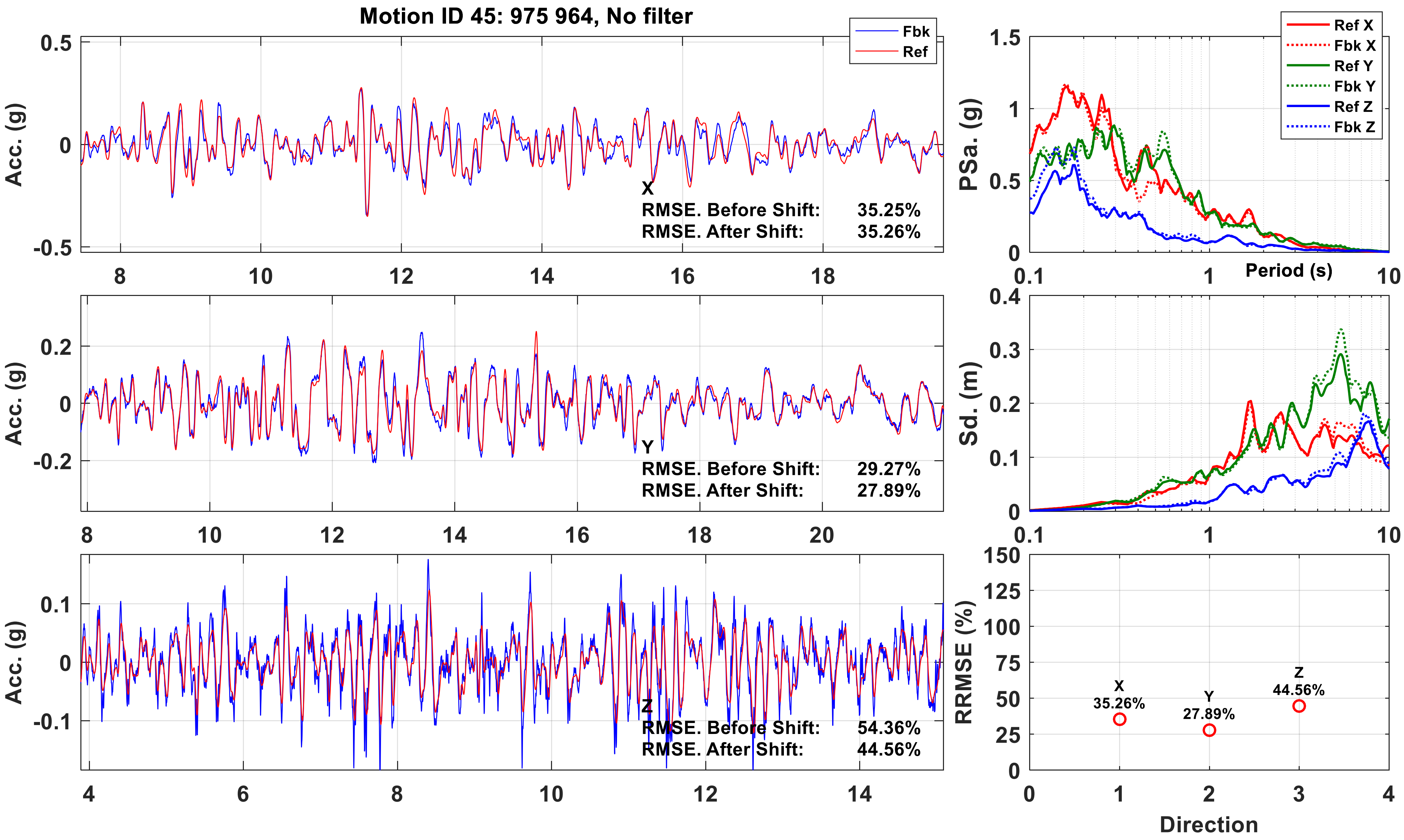
(2018~2021)

Construction of NHERI TallWood Specimen



Target Ground Motion vs. Achieved Table Motion – TallWood Project – Table Loaded with Specimen

1994 Northridge Earthquake Record; Scaling factor = 0.716; Mean return period = 975 years



1989 Loma Prieta Earthquake, MCE_R Level, XYZ (5/17/2023)

THANK YOU !

NHERI@
UC San Diego

For More Information About NHERI@UC San Diego Experimental Facility

- https://ucsd.designsafe-ci.org
- https://nheri.ucsd.edu
- Contact one of the NHERI@UC San Diego team members:
  - Joel Conte, jpconte@ucsd.edu
  - John McCartney, mccartney@eng.ucsd.edu
  - Machel Morrison, mmorrison@eng.ucsd.edu
  - Jose Restrepo, jrestrepo@ucsd.edu
  - Lelli Van Den Einde, lellivde@ucsd.edu
  - Koorosh Lotfizadeh, klotfiza@ucsd.edu

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NHERI

Natural Hazards Engineering Research Infrastructure